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# Humanity and Space

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# Humanity and Space

*A Proposal for the Creation & Development*

*of a Self-Sustained Lunar Colony*

An Interactive Qualifying Project

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In partial fulfillment of the requirements for the

Degree of Bachelor of Science

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## Abstract

Detailed in this proposal is a virtually self-sufficient lunar colony. This paper addresses the design, maintenance, functions, and benefits it would bring to society. Construction and development of the colony are laid out over three distinct phases and the challenges of each phase are discussed. It is the belief of the authors that expansion into the solar system is necessary for the continued survival of humanity, and a lunar colony is the first major step in this expansion.

## Executive Summary

On July 20th, 1969, Neil Armstrong became the first human to set foot on the Moon. Eleven others have since tread upon its surface, with the last mission turning back to the earth on December 15th, 1972. After a hiatus over four decades, it is time for humanity to return. Despite appearing barren and desolate, our nearest neighbor has much to offer to humanity. To make proper use of these gifts however, a permanent human foothold must be established on the lunar surface. With this goal in mind, a plan has been outlined in this document for a lunar settlement spanning three distinct phases: Lunar Outpost, Lunar Station, and Lunar Colony, each with their own sets of goals and challenges that must be overcome if we are to use the moon to its fullest potential.

The first phase consists of a small outpost that will house six astronauts. The outpost will be an inflatable structure located near the Moon's south pole, on the edge of the Shackleton crater. Solar panels backed up by a nuclear reactor will provide power for the outpost. The main goals of Phase 1 are to establish a presence on the Moon and conduct research that will ease the transition into later phases. Phase 1 astronauts will also conduct surveys to determine the sites for future expansion, and construction will begin on infrastructure for Phase 2. Preparation for Phase 1 will begin two years before the arrival of the crew, and the phase will carry on for another two years after the crew's arrival.

Phase 2 comprises of the expansion of existing infrastructure, and construction of additional facilities. The polar settlement will be expanded and, more significantly, a permanent base will be established at the equator to accommodate for a crew which will number 300. This equatorial outpost will be built in a pit in Mare Tranquillitatis. In addition, small-scale mining will begin to obtain materials for in-situ resource utilization. These materials will undergo processing and manufacturing to fabricate various components. The additional infrastructure will include a telescope constructed on the far side in order to monitor Near Earth Objects, and a maglev rail system which will provide efficient transportation between the polar and equatorial bases. A space elevator will also be built to facilitate the inexpensive transfer of cargo between LEO (Lower Earth Orbit) and the lunar surface, and a launch pad will be constructed at the equatorial base to provide a platform for space travel to and from the station. Phase 1 research will be used to build large-scale food growth facilities. The existing power systems will be expanded and research on additional systems begun. Phase 2 will last approximately ten years.

Phase 3 will mainly be focused on expansion of the equatorial settlement, as well as the development of a permanent polar settlement located in a lava tube or excavated tunnel connected to the Shackleton crater. Lunar population and productivity will also be drastically increased. Lunar colonists will be able to live solely off of locally produced food, and will be able to manufacture virtually any basic item they need using local materials. By the end of this phase, the lunar base will transition from a purely self-sustaining goal, to one of further assistance in human exploration and spaceflight throughout the solar system. Rocket production will begin, facilities will expand, and a true lunar spaceport will come to fruition. Phase 3 has no well-defined end date, as it encompasses all future growth of the settlements across the lunar surface, but one of its major milestones will be to house 10,000 people by the end of ten years.

A lunar colony offers extensive benefits to humanity. By colonizing the Moon, humanity will develop technology and gain experience that will prove essential in the colonization of other planets and improve technology on Earth. Useful metals are abundant in the lunar soil, and resources such as Helium-3 and lunar solar power have the potential to sustain the growing energy needs of the Earth. Furthermore, technologies developed to support the lunar colony will also prove useful on Earth. The lunar spaceport will reduce the cost of visiting other planets and facilitate their colonization. Due to its many benefits to civilization on Earth as well as interplanetary colonization, a lunar colony is the logical first step in humanity's expansion into the solar system.

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# Introduction

During the waning years of the Apollo program, NASA devised plans for the creation of a semi-permanent lunar settlement that would allow humans to maintain a foothold on the lunar surface and continue research that could not be performed in the brief windows of the Apollo missions. Shifting public opinion and political circumstances, however, led to the abandonment of these plans and no human has landed on the moon in over four decades. As spaceflight technology improves and our sights turn to targets such as Mars, it is becoming increasingly clear that the moon is the key to achieving our ambitions of becoming an interplanetary species and that NASA's plans must be revived. A permanent lunar settlement would provide a number of benefits to the expansion of humanity, including ample material resources, low-gravity research opportunities, a test-bed for future colonization technology, and a direct stepping stone to interplanetary space in the form of a lunar spaceport.

In pursuit of these goals, we have devised plans for a lunar base whose construction and development will be carried out in three phases. Phase 1 will consist of attaining a foothold on the lunar surface, performing preliminary research, and developing the technology necessary for life on the Moon. Phase 2 will mainly involve the creation and expansion of infrastructure to support the objectives of the lunar base, including mining and processing facilities, a transportation system, and a space elevator. Phase 3 will involve the use of the newly created lunar facilities to facilitate the rapid expansion of the lunar base's population and productivity. By the end of Phase 3, the lunar colony should be a virtually self-sufficient home to roughly 10,000 colonists, whose manufacturing facilities and spaceport will be used to vastly extend humanity's reach throughout the solar system.

# Phase 1: Lunar Outpost

## Goals:

Phase 1 consists of the construction and operation of a small outpost capable of housing six astronauts. The main goal of this outpost is to conduct research that will allow for a smooth transition to a larger settlement and to provide a location for humans to oversee the construction processes. Preliminary research will include studies on the effects of the lunar gravity on human and plant growth. Much of the Phase 1 research will focus on the lunar regolith. Astronauts will determine its feasibility for plant growth, study its composition, and devise methods to extract the useful materials present. Phase I will also test automated technology and construction techniques before applying them to a large-scale settlement. Additionally, surveys of the lunar landscape will determine sites for a telescope, launch pad, and maglev track. Then, construction will begin for expansion into the later phases.

## Location:

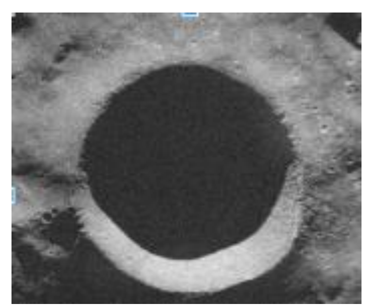

*Figure 1: Overhead view of Shackleton Crater*

The initial outpost will be located at the rim of the Shackleton crater at the Moon's south pole. This location is exposed to nearly constant sunlight, so the facility can run on solar power. In addition, it does not experience the extreme temperature fluctuations that are present elsewhere on the moon, which can range from roughly +150 °C during the daytime to -170 °C during the night. The average temperature of the rim of the crater is -73 °C (American Museum of Natural History, n.d.). The team of astronauts and robots will be responsible for determining if there is a lava tube in the area for a permanent structure. If not, the permanent structure may be built into the sides of this crater to protect from space weather and micrometeorites.

| Location | Features | | | | | Rating |
|---|---|---|---|---|---|---|
| | Radiation Protection | Temperature Fluctuation | Escape Velocity | Sunlight | Good for Overseeing Phase 3 | |
| Pit in Mare Tranquillitatis | 3 | 1 | 3 | 1 | 1 | 9 |
| Shackleton Crater (surface outpost) | 1 | 3 | 1 | 3 | 3 | 11 |
| Pit in Mare Fecunditatis | 3 | 1 | 2 | 2 | 2 | 10 |

*Figure 2: Location trade study (controlled convergence method)*

## Structure:

The structure of the outpost will be one or more inflatable habitats. These habitats will be covered in lunarcrete (a concrete-like material formed from lunar regolith and an adhesive) for

*Figure 3: Inflatable habitat with regolith coating (ESA, 2013)*

radiation and micrometeorite shielding (Roberts, 1992). Small solar arrays and a small nuclear reactor will serve to provide the outpost with power. Should significant Lunarcrete production prove unfeasible, solid bricks of sintered regolith material (regolith that has been formed into solid blocks through heat treating) could serve as a sufficient replacement. The following facilities will be required for a fully operational base: life support systems, living and exercise quarters, laboratory, storage for food, water, equipment, and power, robot maintenance facility, and external power generation facilities. In addition, once the main structures are properly set up, a small area below one of the structures will be excavated and used to protect the crew and sensitive electronics in the event of a solar flare. The main habitats will be designed in a modular fashion, so they can be used in whatever manner the crew requires at any given time.

## Construction:

Construction of the outpost will be carried out in a number of distinct phases. First, a small lander and rover will be sent to the predetermined site to survey the area and confirm its viability as an outpost location. They will also test the feasibility of small-scale lunarcrete creation and deployment. Next a number of robotic rovers and landers will be sent to the outpost site to begin gathering regolith and processing it in a number of ways. These robots will test the use of regolith as a base material in 3D printing (as lunarcrete), the sintering of regolith into blocks of building material, and the separation of water and other materials from regolith, to be stored and retrieved by the crew upon arrival. Next, work will begin on construction of a large solar power plant, and a small nuclear reactor will be landed to provide adequate power as the solar plant is under construction. Once these power facilities have been landed and shown to be in proper working order, the main inflatable base structures will be landed, inflated, and connected to the power generation facilities. If lunarcrete production was successful, robots will then begin to coat the structures with the material. Once this step is complete, additional supplies will be landed at the outpost site. Shortly afterward, the crew will land, retrieve the prepared supplies, and finish setting up the base, including excavating and setting up the emergency shelter.

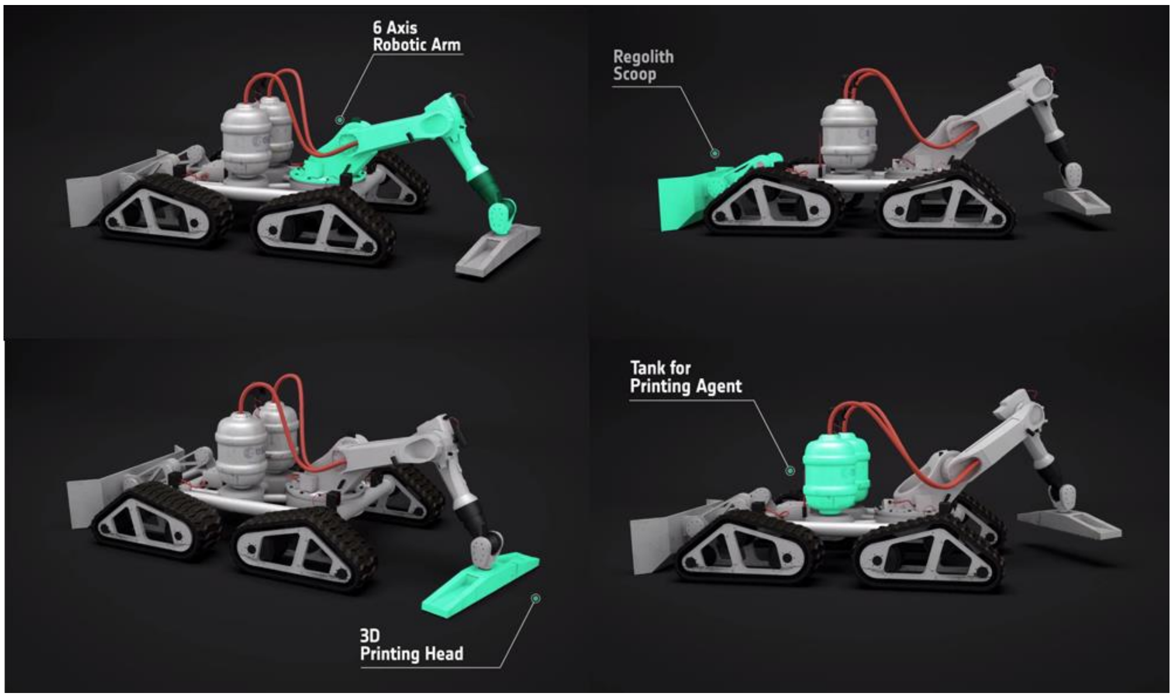


*Figure 4: Concept for a regolith collection, processing, and printing robot (ESA, 2014)*

## Life Support:

The life support systems within the main habitats will be derived to a great extent from those on the ISS, with some modifications to adjust for the lunar environment. The two major pieces of the life support system will be the air recycling and monitoring, and water recycling and generation systems, but there will also be temperature and humidity controls and fire detection and suppression systems in place. The water reclamation system will recycle water from liquid waste and other water sources used by the crew, as well as excess water vapor from the temperature and humidity control systems. On the lunar surface, water can also be acquired via the reaction of hydrogen with the abundance of oxides found within the lunar regolith, as well as extracted from lunar ice if possible. The hydrogen used in this process will need to be Earth sourced. In the case of the air systems, there will be included subsystems designed to filter out carbon dioxide and other trace contaminants from the air as well as analyze the composition of the habitat air for any irregularities. On the subject of oxygen generation, some of the water resulting from the water

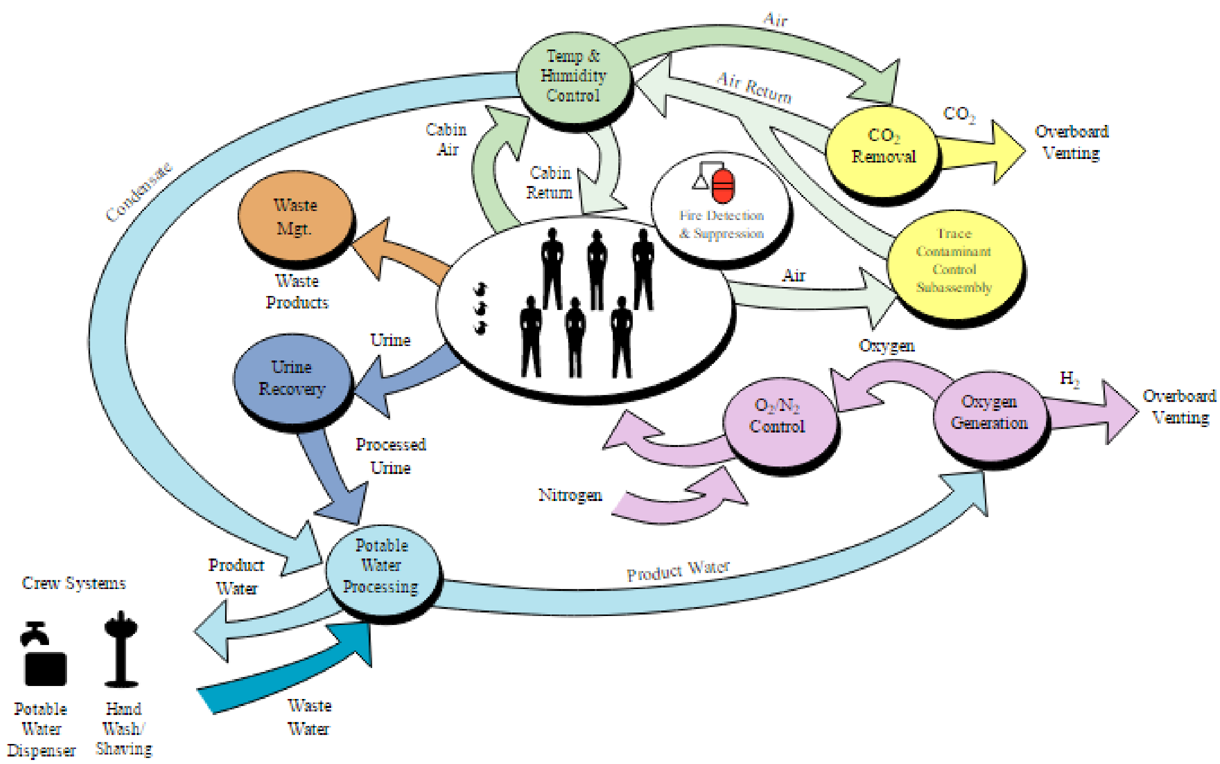


*Figure 5: Diagram of the flow of materials within the ISS life support system (Barry, 2000)*

generation process outlined above can be diverted and electrolyzed into oxygen to be pumped into the habitat atmosphere, and hydrogen to be used again in the water generation process (Hypes, 1992). In addition, chemical oxygen generators will be on standby in all habitats to provide temporary supplies of oxygen in the event of system failure. There will also be a dedicated temperature and humidity control system to keep habitat atmosphere within acceptable bounds. The fire suppression and detection systems will be mainly comprised of handheld chemical extinguishers in each individual habitat section and a few automated suppression systems in important areas.

Temperature inside the habitat will be controlled through a combination of multilayer insulation (MLI) and regolith coating. For MLI, the structure will be covered in multiple layers of fine reflective material with small spaces between each layer. This will provide protection against heat exchange through radiation. Additionally, the structure will be covered in a 2-meter thick layer of regolith for insulation. The combination of MLI and regolith coating will lower heat gains to .08 kW during the day and heat losses to 0.17 kW during the night (Eckart, 1996, p. 78). Coating the structure with dark material will allow absorption of heat from the sunlight. The ground around the structure could also be coated to increase ambient heat. An air conditioning system together with ceiling panel cooling and forced convection cooling systems will be used to maintain the temperature of the base around 21° Celsius (Simonsen et al, 1992).

## Power:

One or more nuclear reactors capable of producing 100 kWe will initially power the early development of the facility. The three reactors under consideration are two uranium-fueled reactors SP-100 and HOMER-25, and the liquid fluoride thorium fueled Space Molten Salt Reactor (SMSR) design. All of these reactor types are still in varying stages of design phase. Of these, the SMSR has significant advantages over the other designs. This design can use a number of fuels, and a Liquid Fluoride Thorium fuel will be used in this situation. This is due to the fact that Thorium is 3 times more abundant than Uranium ("World Nuclear Association"), which will bring fuel costs down. This is the most significant advantage this design has over the SP-100 and HOMER-25 designs, as both use solid Uranium fuel. In addition, data from the Lunar Prospector shows thorium deposits on the moon in Mare Ibrium, Mare Oceanus Procellarum, and the South Pole-Atkin Basin (Lakdawalla, 2011). This thorium could potentially be used to produce fuel in-situ to power the SMSR during later phases, thus decreasing dependence on the earth. A more in depth comparison of the three reactors under consideration can be found in Appendix A.

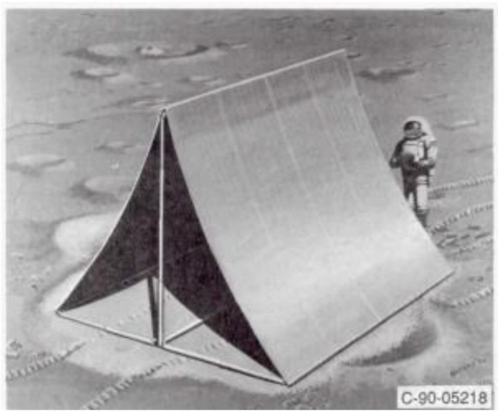

*Figure 6: Self-Deploying Tent Array (Hickman, 1990)*

The SMSR will be installed 2 years before the crew's expected arrival date, and will be the primary power supply for the preparatory activities until completion of the lunar solar plant (LSP). Soon after the emplacement of the nuclear reactor, preparatory work will begin on a 100 kWe LSP. Located at the "peak of eternal light" at the rim of the Shackleton crater, which experiences sunlight for 84% of the year (Noda, p. 4), the LSP will eventually provide a permanent source of power. The basic unit of the LSP will be a self-deploying (Hickman, 1990, p. 4) array, the design of which is based on the International Space Station (ISS) solar arrays. These arrays each measure 33.5 m by 11.6 m, and consist of 32,800 photovoltaic cells (Boeing, p. 3). The total area covered is 388.6m$^2$ but this area is a downward biased estimation as the ISS uses cells of a lower efficiency. The array will have triangular shape sloping downwards with a 60° angle to maximize the incidence of sunlight (NASA, 1988) Tracking array technology that can change angle in accordance with the incidence of sunlight was considered, and although it would have a greater efficiency than a static array configuration, current technologies will not be cost effective on such a scale. Gallium Arsenide photovoltaic cells will be used due to their high conversion efficiency and temperature resistance relative to other types available at this time (Trochynska, 2009). Specifically, InGaP/GaAs tandem solar cells will be used which have efficiencies of 37.9%, the greatest among current models (Green, 2014, p. 702). During future phases, the LSP will expand using more cost-effective tracking array technology and more efficient solar cell technologies such as quantum dots, which are discussed in Phase 3 (Appendix A). The arrays will be placed 15m apart in 5 rows to prevent them from overshadowing each other. Each array can generate 11 kWe so 10 such arrays will be installed to provide a nominal power capacity of about 100 kWe during daytime. Regenerative Hydrogen-oxygen fuel cells will be installed to store energy produced by the solar plant during the day for use during the night, which can last a maximum of 168 hours at the Shackleton crater. The fuel cells will be operating on half power during the night so night power usage will need to be minimized. Scheduling all automated tasks operating at a power of greater than threshold wattage during the day will ensure this. Power recycling systems will be used to increase efficiency. The required backup power for maintaining life-support systems will be in the order of 3 kWe per crewmember (McGinnis, pg.1), hence 18 kWe for 6 crewmembers. 18 Lithium ion batteries will be required to produce this power, and another 18 will be kept on standby for redundancy. A123 System Energy Storage Li-Ion batteries will used due to their high energy density (Horiba, 2014, p. 9).

Radiator systems will be used to cool all power systems, and a power management and distribution system will monitor power supply to all electrical components. As in terrestrial electric transmission, power will be transmitted at high voltage to cut transmission losses, and transmission lines will be buried under 2m of regolith for thermal insulation (Eckart, 1996).

## Crew Composition:

Six astronauts of various technical backgrounds will make up the crew. The crew will be divided into a Research Team and an Engineering Team comprised of three astronauts each.

The Research Team will consist of a medical doctor, a geologist, and a botanist. The primary function of this team is to conduct the research laid out in the Phase 1 goals. The doctor will perform research on the effects of the lunar environment on humans and human development, as well as provide medical care to the other astronauts. The geologist will study and analyze the lunar regolith, research methods for extracting useful materials, and survey the local geological features to determine suitable sites for future construction. The botanist will study plant growth on the moon to determine the most effective methods for growing food. This research will focus on aeroponics as this is the most water-efficient method of plant growth.

The Engineering Team contains a space systems engineer, a mechanical engineer, and an electrical engineer. The electrical engineer will maintain the solar power plant, the nuclear reactor, and power management and distribution systems. The mechanical engineer will troubleshoot any mechanical problems with the facility and its supporting equipment. The space systems engineer will oversee and maintain specialized equipment such as space suits, lunar rovers, and life support systems. In addition to these support and troubleshooting duties, they will use the research team's results to design new technologies that will aid in the later phases. They will also use their direct experience with the challenges of lunar living to assist in the design of habitats for later phases so that future residents can live more comfortably.

For ease of communication with Earth, the outpost will follow a 24-hour day/night cycle with times in GMT. Daily exercise will also be mandatory for all crewmembers to counteract the degeneration of muscle and bone. Crew will be rotated out in groups of three every six months so that the experienced crew can guide the newer crew in the minutiae of life on the outpost.

## Surface Transportation:

The Phase 1 astronauts will need access to surface transportation in order to survey the area surrounding the outpost, collect regolith samples for study, and to get away from the habitat in case of emergency. Two rovers based on NASA's Lunar Electric Vehicle design will provide surface transportation for the astronauts. These rovers have pressurized cabins so the astronauts can work comfortably inside without having to wear a spacesuit. Spacesuits are carried on the outside of the vehicle and can be donned in a matter of minutes, giving the astronauts quick access to the lunar surface. With these features, the rover can be used as a mobile laboratory and astronauts can conduct initial studies without having to return to base. A thin layer of water ice protects the cabin from harmful radiation. The rover is also equipped with a docking module, so astronauts can enter the rover directly from the habitat. These rovers would allow the crew to survey areas up to 240 km away from the habitat. For exploration of the local area, rovers are typically crewed by two astronauts. In case of an emergency in the habitat, each rover can independently provide life support for up to four astronauts for 72 hours (National Aeronautics and Space Administration [NASA], 2008).

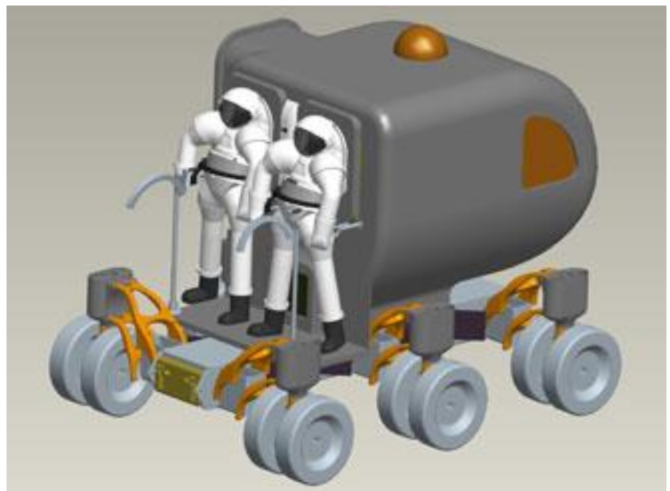

*Figure 7: Lunar Electric Rover (NASA, 2007)*

In addition to the two rovers, longer range "shuttles" with thrusters will be designed to take off and land multiple times, allowing astronauts access to locations across the lunar surface. Such shuttles would be powered by a hypergolic propulsion system, as well as a basic RCS system. They would be able to transport two crewmembers between the polar base and locations near the equator. They could also serve as backup escape craft and be able to reach lunar orbit and rendezvous with the cislunar transfer craft waiting there.

## Space Suits

The rovers are also compatible with the space suit that has been chosen for this mission. Apart from this compatibility, great care was taken in the process of deciding upon what type of space suit to use. Below, a controlled convergence method trade study is shown to illustrate the procedure by which a space suit was chosen. This shows a qualitative comparison between four types of suits. While down the line, different space suits may be needed for different tasks as they arise, the hybrid space suit appears to be a suitable choice for the beginning of this mission for several reasons. They are 30 pounds lighter than the original EMU, and have superb efficiency in the don/doff procedure due to the "step-in" design, and much better maneuverability (especially in the lower torso region). A suit of this description would be similar to the NASA's z-2 suit which has the described step in don/doff procedure

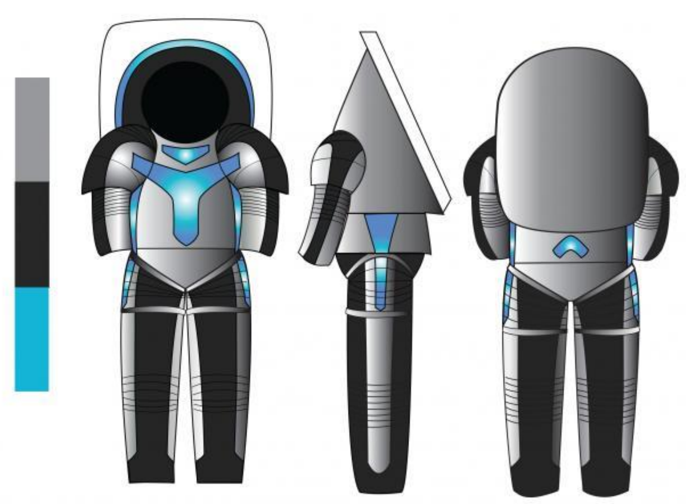

*Figure 8: Hybrid space suit design ("NASA's New Zombie Z-2 Suit Is Good For Godzilla")*

and is compatible with the rover (Wall, 2014). To further explain the rankings given, each design was discussed thoroughly. All designs had equal rankings in pressurization except for the MCP which can still not be trusted to give uniform pressurization throughout. While by the time this plan comes to fruition MCP may be a viable option, the problem of using anything other than the balloon type pressurization seen in all working space suits and opting for a mechanical system, still hasn't been solved. The hybrid suit also solved the age old issue of the lengthy don/doff procedure ubiquitous with extravehicular activity. The improved capability of the hybrid suit makes it almost impossible to match with the other suits disregarding other design issues that prevent quick don/doff procedures. Maneuverability is certainly the worst in the Apollo age soft suit given its bulky balloon-like design. If other shortcomings of the MCP could be resolved, it would perhaps take the lead in this area, where the rigid body of the hard suit also fails (Malik, 2007). The hybrid suit once again is a viable option here, however, as it takes from both the soft and hard suit designs to make maneuverability, as discussed before, much better in most regions, particularly the torso region.  While not ranking best in durability or weight, both were in a neutral range and considered to be a drastic improvement over the Apollo aged suits. Given these reasons, the hybrid suit scored the best rank among the choices.

| Design | Desired Features | | | | | Rating |
|---|---|---|---|---|---|---|
| | presurization | ease of don/doff | manuverability | durability | weight | |
| hard suit | 3 | 2 | 2 | 3 | 1 | 11 |
| Soft suit | 3 | 1 | 1 | 2 | 1 | 8 |
| Hybrid suit | 3 | 3 | 3 | 2 | 2 | 13 |
| Mechanical counter pressure suit (MCP) | 1 | 1 | 3 | 3 | 3 | 11 |

Key:
1 = poor
2= neutral
3= excellent

*Figure 9: Space suit selection trade study*

## Backup Systems & Contingency Plans:

In the event of emergency there will be a number of systems in place to ensure the safety and survival of the crew. Radiation is one of the most prominent dangers to the health of the crew, and the main habitats will be constructed to block out a significant portion of the incoming solar and interstellar radiation that will be constantly bombarding the lunar surface. In the event of an incoming solar flare, the crew will retreat to a shelter excavated below one of the habitats which will be a structurally supported basement consisting of a minimum of 5 meters of regolith between it and the surface. The constant threat of micrometeorites will also be mitigated by the thick regolith walls coating the habitats and EVAs will be kept as short as possible to reduce the direct risk to the crew. In the event of any kind of medical emergency, there will be a doctor on station and all crew will have extensive medical training.

Many different sources of power will be used so as to greatly reduce the chances of major power loss. Nuclear power will provide backup to the Lunar Solar Plant (LSP), and Lithium-Ion batteries will provide last resort emergency backup for life support in case of failure of both power systems. In the event of a fire, all crew members will be trained in fire suppression techniques and both portable and automatic suppression systems will be present in the final outpost design. In the event of a main habitat becoming unusable for any reason, the crew will have the other habitats to retreat to. The rovers are also mobile and easily accessible options for shelter. In the unlikely and unfortunate event that the outpost must be evacuated, at least two escape vehicles will be on standby to launch into lunar orbit where they will rendezvous and dock with an orbiter, which will return the crew to Earth. The escape craft will be used and replaced on crew rotation to reduce their chance of failure.

## Schedule:

The precise construction schedule will be carried out as such: Initial preparations will begin two years before the arrival of the crew. First, remote operated robots will determine the exact locations of the outpost and power facilities. After three months or so of surveying, the nuclear reactors and solar panels will be delivered and assembled by robots. The landing and setup of the nuclear reactor will take place over the next three months, and the solar arrays will then be constructed over a period of around six months. The power management and distribution systems will be deployed after this and checked for any malfunctions over the course of the next few months. Next, the belowground shelter will be excavated and the inflatable structures will be delivered, inflated, and printed over with regolith. This process will take on the order of two to three months. The next three months will be spent meticulously checking all areas of the habitats for air leaks, temperature imbalances, and other defects. Once that is completed, the crew will land along with the remaining necessary supplies and finish setting up the base. They will then spend the next three months performing basic experiments and begin the process of surveying locations for Phase 2. Within the first two years of habitation, research will be carried out and the first steps of construction on infrastructure for Phase 2 will begin. Supplies for the preparatory phase could be delivered in five flights of the SLS, using a large upper stage to provide the delta-V required for lunar landing. The crew and some smaller supplies would arrive on the sixth and seventh flights.

Flight Schedule:

| Flight no. | Cargo | Total Mass/kg |
|---|---|---|
| **Flight 1** | Robonaut 2 teleoperated rover (150 kg) (NASA, 2010) | 150 |
| **Flight 2** | Nuclear reactors (5000kg) - estimated based on weight of other small reactors<br>Power management and distribution system at 19kg/KWe (4000kg) (Eckart, 1996, p. 69)<br>Lithium-ion batteries (100kg) (Horiba, 2014, p.9)<br>10 Solar Arrays at 10 kg/m$^2$ (4000kg) (Eckart, 1996, p.60) | 13,100 |
| **Flights 3-4** | Regenerative Fuel Cell Storage and radiator system - (45000kg) (Eckart, 1996, p. 74) | 45,000 |
| **Flight 5** | 2 Roving Space Exploration Vehicles (at 3000 kg each)<br>Inflatable habitat and robots to set up (estimated 10,000 kg) | 16,000 |
| **Flight 6 & 7** | 2 Orion Capsules w/ lander: (at 20,000 kg each)<br>• Would carry both crew and supplies in each<br>• Would work better for rotations of 3 crew at a time | 40,000 |

*Figure 10: Phase 1 Flight Schedule*

<u>Gantt Chart of Phase 1 Schedule:</u>

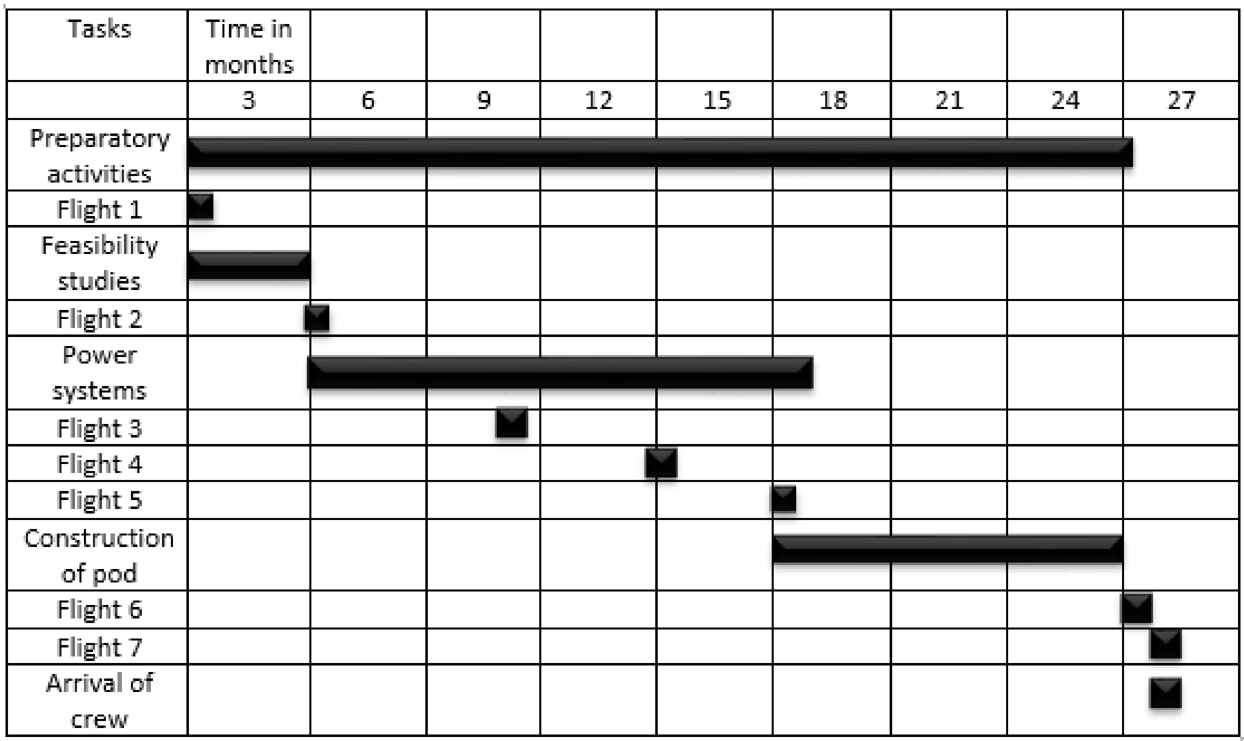


*Figure 11: Gantt Chart of Phase 1 Schedule*

## Costs:

Costs for such a large scale project are difficult to estimate without direct access to experts on the subject, but the following figures were produced by rough approximations: $35 billion would be required for the construction of the base, including the R&D costs for the specialized equipment and technologies used in base construction. The six largest flights required to transfer materials to the base using the SLS system would cost roughly $30 billion or $5 billion per flight. Yearly maintenance of the base, including crew rotation and resupply missions would cost approximately $11 billion per year. Over a two year lifespan, a lunar outpost of this type would cost roughly $87 billion, roughly equivalent to the total cost of the US portion of the ISS.

## Phase 2: Lunar Station

Goals:

Where Phase 1 revolved around creating a foothold on the lunar surface, Phase 2 revolves almost entirely around putting in place the infrastructure that will be required for mass settlement of the moon and its role as a spaceport and rocket manufacturing location. Our goals for Phase 2 of the lunar colonization process are as follows:

- Establish permanent equatorial settlement
- Expand polar settlement
- Begin lunar prospecting and mining
- Construct:
  - Lunar material processing and construction facilities
  - Far-side observatory
  - Maglev rail system between equator and polar outpost
  - Launch pad at equatorial settlement & polar settlement
  - Space elevator to service settlements
- Expand solar & nuclear power facilities
- Begin large scale food growth
- Expand total lunar population to 300 by start of Phase 3

## Equatorial Settlement:

The equatorial settlement will be located in a pit in Mare Tranquillitatis. Pits are believed to have lava tubes attached to their perimeters and would provide the ideal place for a permanent outpost. This outpost will be built in a modular fashion so that crew can be brought in several phases and the area can be optimized for expansion over time.

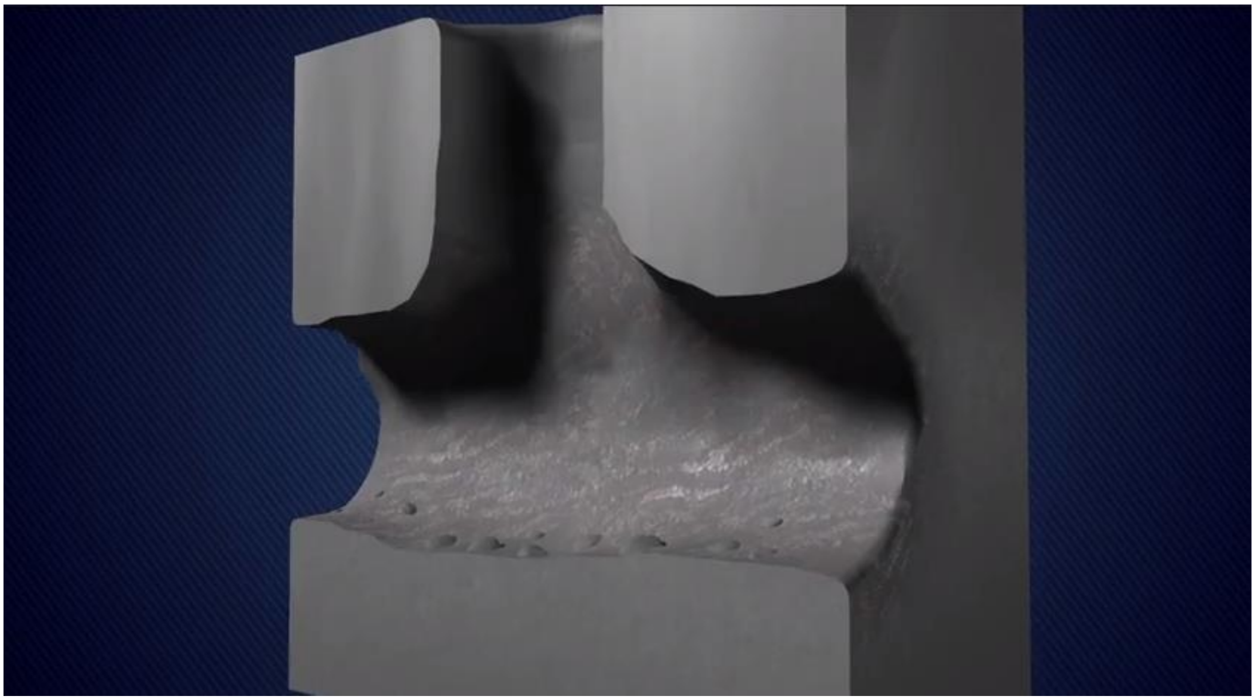

*Figure 12: Cross-section of Pit Connected to Lava Tube (Chase & Meany, 2015)*

The basic plan is a 13 step construction sequence:

1. Create inflatable surface observation deck to oversee automated construction
2. Build elevator shaft
3. Excavate tube
4. Drill escape hatches down to the lava tube
5. Use microwaves to heat seal the sides (done simultaneously with steps 3 and 4)
6. Build support beams
7. Use lunarcrete to build floors and air locks

8. Build homes on first floor
9. Pressurize first floor
10. Move in first group of people
11. Complete middle and bottom floor
12. Pressurize middle and bottom floor
13. Continue expansion and move-ins

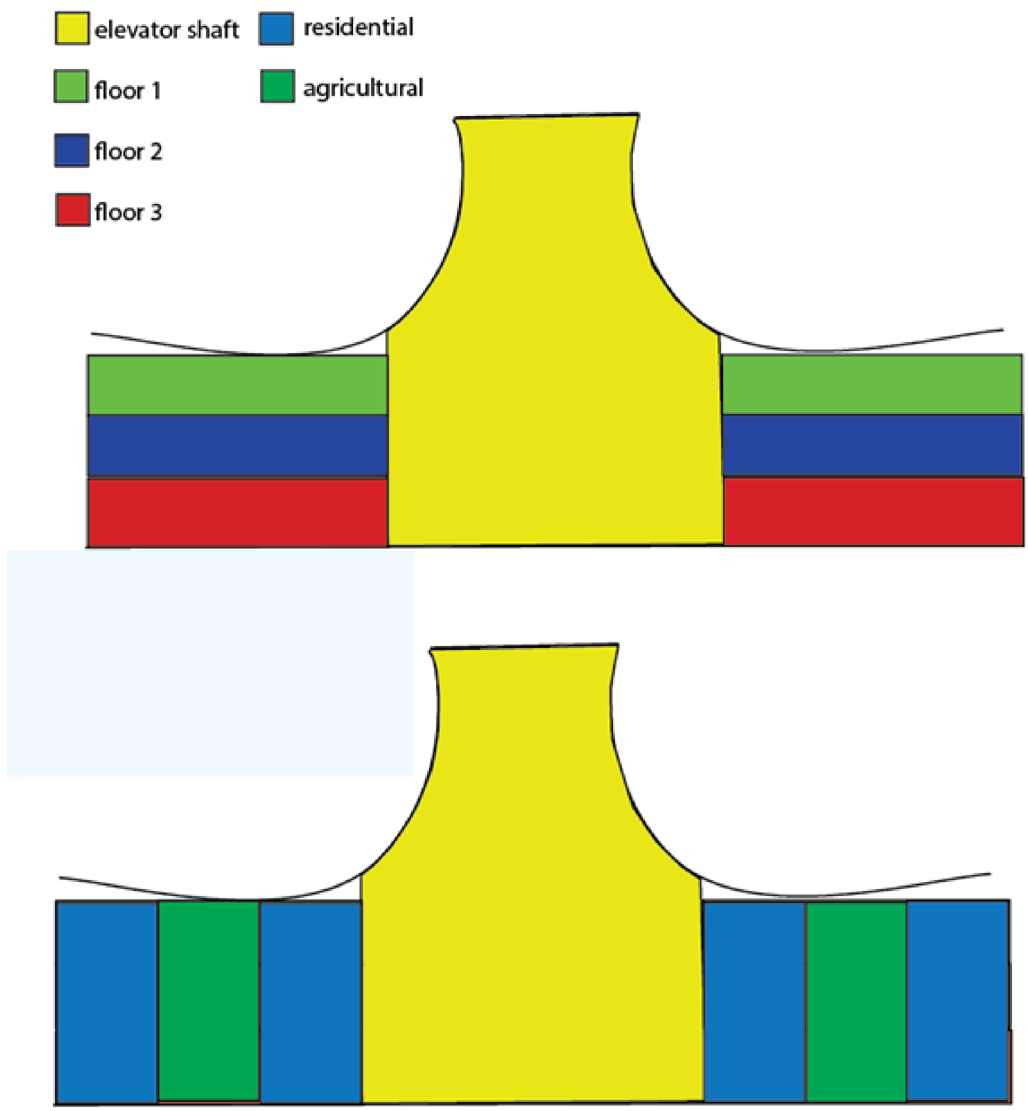


*Figure 13: Sketch of habitat layout*

## Population & Facility Expansion:

In order to facilitate the expansion of the base, the power systems must be expanded accordingly. During Phase 2, the capacity of the solar power plant will be steadily increased to 500 kWe, and the number of fuel cells will be increased to provide a nominal power of 250 kWe during the lunar night. This will be accomplished by switching to tracking arrays that can shift orientation in accordance with angle of incidence of sunlight (NASA, 1988, p. 5). The nuclear reactor will also be expanded to 500 kWe in order to maintain a reliable backup system. This additional capacity will also be used to support the construction and operation of various new facilities, including the space elevator and maglev train. At the onset of Phase 2, primary research will begin on nuclear fusion of Helium-3 and microwave transmission of power. Depending on the advancement of fusion technology, a small experimental reactor similar to the one in use at the University of Madison- Wisconsin (refer to Appendix A) will be used to generate power from nuclear fusion of lunar Helium-3. In addition, experimental microwave generators will be used to transmit power over varying distances on the lunar surface, and when the technology readiness level increases, to various lunar facilities. Primary research will also be carried out into the use of lunar Thorium for the Space Molten Salt Reactor (SMSR), and the efficiency of the LSP will be increased by using solar sails and/or free flying mirrors based on Phase 1 research.

## ISRU:

The in-situ resource utilization (ISRU) process will be used to produce materials for the expansion of the existing base and the solar power plant, and the construction of the equatorial base, launch pad, telescope, and maglev train. During Phase 2, small scale ISRU capabilities will be developed to prove economic viability. The ISRU process will reduce the mass of payloads delivered from the earth, which will in turn lead to a drop in launch costs. Production of life support consumables, and the capability of repairs and construction on the lunar surface will also reduce the risk to the inhabitants by reducing their reliance on the Earth, and provide greater versatility in terms of missions and research (Sanders, 2005). Power systems can also be expanded using locally produced solar cells, and lunar helium-3 and thorium. ISRU will also enable the recycling of resources, thus increasing efficiency. Potential material yields from the lunar surface include Iron, Aluminum, Calcium, Magnesium, Silicon, Titanium, volatile gases including Hydrogen, Oxygen and Helium-3, and water from potential polar ice deposits (Taylor, 1992).

## Lunar Mining:

In order to adequately take advantage of the opportunities that ISRU presents, new methods of recovering materials from the moon will need to be developed. The surface of the moon is a challenging environment where mining methods that are suitable for Earth use are not viable. The vacuum environment causes many industrial lubricants to outgas and be rendered ineffective. The thick, abrasive dust that coats the lunar surface causes serious wear and tear on equipment, especially in machines with many joints and moving parts. Modern mining equipment is also unable to withstand the extreme temperatures near the lunar equator. The near constant radiation environment also poses a challenge in the impeding effects it can have on the electrical and computer systems that would play a huge part in the efficient running of any lunar mining operation. Micrometeorites also pose a small but ever present risk to large exposed mining equipment. Finally, while the low gravity environment is a boon for bulk transportation of mined materials, it is an impediment in that it is much more difficult to provide a sufficient counterweight to keep the mining equipment stable while they perform their tasks. In addition, current mining operations on Earth are hugely energy intensive, require extremely large and heavy equipment, and an enormous amount of human oversight and maintenance (A Review of Possible Mining Applications in Space, 1993).

One way of sidestepping many of the issues listed above would be by concentrating the bulk of the mining operation below ground, mining the solid rock instead of the loose surface regolith. In addition to the avoidance of many of the issues such as temperature and radiation, underground mining would also leave spaces below ground that could be easily converted to livable human habitats by sealing the walls by means of microwave heating. Tests have been performed in sealing basaltic rock with this tactic. A microwave generator suitable for the task would use about 80 kW of power and be able to seal ~1 $m^2$/h of excavated area (A Review of Possible Mining Applications in Space, 1993). As mining operations expand, more and more living space would free up, supporting a growing population.

On the other hand, surface mining offers a few advantages. The lunar regolith, being in powder form, would require less effort to process into useful materials. In addition, Helium-3 is a major resource found in the regolith and not in the underground rocks. In addition, the lunar regolith is highly compressed just 30 cm below the surface (A Review of Possible Mining Applications in Space, 1993), allowing it to be more easily transported in bulk.

Mining operations on the lunar surface will start with surface mining within Shackleton Crater to protect the equipment from radiation, micrometeorites, and temperature changes. This phase of mining will mainly consist of simple machines that will gather regolith from the surface, transfer it to large storage bays, and then compact it as much as possible for transportation purposes. There are a number of possible methods of material transportation including conveyer belts, cable trams, magnetically levitated containers, and ballistic throwing, each of which will need to be investigated in detail to determine their feasibility for the task. As Phase 2 progresses, underground mining operations will begin both at the polar station and equatorial station. At the polar station, excavation will begin into the sides of the crater, close to the existing habitats. At the equatorial outpost, excavation will focus on the smoothing of the sides of the selected lava tube, as well as digging into its sides. In the beginning, excavation will be relatively slow and mainly used to test different types of machinery to determine which technology will be optimal for expanded use. A number of different mining technologies will be tested, including modified terrestrial equipment such as road headers, and hydraulic rock splitters, as well as experimental techniques such as laser cutting and microwave fracturing. Once the optimal method has been determined and the necessary equipment shipped to the excavation sites, mining operations will be expanded accordingly.

## Lunar Materials Processing & Production:

Early in the phase, two pilot facilities will be constructed using inflatable structures covered in regolith. The exact location will depend on the feasibility studies carried out during the previous phase, but the tentative location of the pilot facilities will be the rim of the Shackleton crater, where they will be in close access of the resident engineers. Towards the end of Phase 2, these will be replaced by permanent structures built using extracted lunar materials including lunarcrete. Surveys and feasibility studies will also be carried out to determine the most suitable location for processing/manufacturing facilities large enough to sustain the base. Locations such as pits and lava tubes will be considered, as they can provide shielding from radiation and micrometeorites.

The regolith brought to these facilities will undergo two steps. In Step 1, the regolith is to be carried to the small processing facility from the mining site. Cable trams, or a sled-and-tether approach which move along a tether system, will be used for transport from mining to processing facilities during the early development of the facility. They can be used over a variety of distances depending on the length of the tether and require less infrastructure compared to conveyer belts, while using almost the same power (Faierson, 2012, p. 287). Conveyor belts are used within the facilities. Solid rock from the subsurface excavation is crushed on site, after which the regolith is beneficiated by separating the finer part from the coarser part in two steps - first, mechanically using a coarse sieve, and then by electrostatic separation. Ilmenite is extracted at this stage through electrostatic separation (Ruiz, pg.1) and carried to a hopper in the manufacturing facility for storage. The beneficiated regolith is then carried to reactors where the extraction occurs.

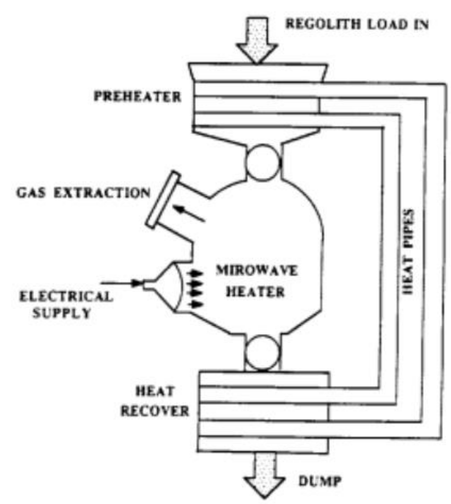


*Figure 14: Pressurized regolith heater (Wittenberg. 1992)*

First, it is heated to very high temperatures specific to each gas. Helium-3 requires a temperature of 750°C (Wittenberg, 1992) and Hydrogen requires 900°C (Robins, 1988). Microwave heating will be used, as research shows that lunar soil contains Fe in nanophase, which combines well with microwaves (DiGiuseppe, 2009). Hence, using high frequency microwaves to heat the regolith will prove more efficient in terms of energy and time as compared to conventional sources (Taylor, 2004). The volatiles, which include Hydrogen, Helium-3, Sulfur, Fluorine and some Oxygen, are released from the heated regolith and captured for use. The entire process will take place in a closed pressurized system as shown in the Figure 14, and any volatiles lost during the extraction process will be captured and rerouted to another reactor for further separation. Then, the oxygen extraction process begins. Three methods were considered for this (Appendix A) and of these, molten electrolysis of silicates and oxides has the greatest energy efficiency and oxygen yield. In this method, silicates and metal oxides are reduced to form oxygen and metals.

In Step 2, the metals are transported to the nearby Manufacturing facility using cable trams. Hydrogen and oxygen is transported to be stored in fuel cells, and Helium-3 is taken to the research facility. Aluminum, Iron and other metals are used to make parts for construction and repairs, and calcium may be used to 'fix' portions of the excess carbon dioxide produced in the base, forming calcium carbonate that can be used as cement. Solar cells will be manufactured using only lunar resources, with conversion efficiencies as high as 11% (Ignatiev, 2012). These will be less efficient but more cost-effective than earth-based solar cells, and can be used for repairs or backup arrays. Ilmenite also undergoes a reduction reaction with hydrogen to produce water at 900-1050°C (Eckart, 1996): $FeTiO_3(s) + H_2(g) = H_2O(g) + TiO_2(s)$. This water can be stored in fuel cells and converted to Oxygen as required, which will be a secondary source of oxygen as the base grows. The remainder of processed regolith and coarser rejected regolith is sintered using microwave heating to produce bricks for construction of habitats or various facilities.

The greatest of the hurdles associated with ISRU is the lack of knowledge of how resources are spread out under the lunar surface. This will be overcome during this phase through extensive surveying and mapping of all potentially useful resources. The lunar dust and micrometeorites also pose risks to the moving parts of the mechanical conveyance systems by lunar dust. During Phase 2, the ISRU system will be operated at a small-scale for which mechanical conveyance will be cost-effective, but during later phases, using a pneumatic system would be advantageous as it has no moving parts and is contained in a closed pressurized volume, thus minimizing exposure. It would also allow beneficiation to occur during transportation, hereby minimizing the mass of the beneficiation system and the time required (Mantovani et al, 2010). Another hurdle is the low efficiency of current extraction methods, especially for oxygen and water. This will be heavily researched during this phase. Due to the dearth of lunar soil samples, simulants or synthetically created materials that are thought to simulate the behavior of lunar soil are used for research. It has been argued that the simulants in use today do not accurately replicate the unique qualities of regolith (Taylor, 2010). Therefore, the research carried out on the moon will yield more accurate results than current research. The economic viability of the ISRU system is also unproven, and will be proven during phase 2 by demonstrating small-scale ISRU capabilities using cost-effective mining, processing and manufacturing methods, thereby paving the way for large scale ISRU. Finally, the largest hurdle is the large expenditure of power required during the various stages - from the transportation of regolith between sites to the microwave heating to high temperatures - which will be overcome by the recycling of energy within the ISRU system and the expansion of power systems of the base.

## Lunar Space Elevator:

A key piece of infrastructure for the lunar station will be one or two space elevators that will provide cheap, reliable transport between the L1 and L2 Lagrange points and the lunar surface. A typical space elevator design calls for a cable reaching up from the equator of a planetary body to a counterweight beyond that body’s equivalent of geosynchronous orbit, along which small vehicles will climb to and from the surface (Appendix B). On a moon, however, due to the gravitational dynamics of the larger body that it orbits, the cable would have to stretch through either the L1 or L2 Lagrange points, where the gravitational forces of the two bodies cancel out. Many concepts for an Earth based space elevator have been proposed, but they all run into a major stumbling block in the form of the cable material. For an Earth based elevator to work, it would require materials like carbon nanotubes that are still in experimental development, and are currently impossible to mass produce. For an Earth based elevator, the geosynchronous orbit that the cable would lie around is 36,000 km above the Earth. In the Earth-Moon system the L1 Lagrange point lies approximately 56,000 km from the center of the Moon, towards the Earth and L2 lies approximately 62,500 km from the center of the moon away from the Earth, so the cable in a lunar space elevator (LSE) would need to be much longer than that of an Earth based space elevator. Due to the reduced gravity and lack of atmosphere, the cable of an LSE could be made of common industrial fibers, such as Kevlar, M5, or Spectra, despite the longer cable. In addition, while an Earth based elevator would require a tapered cable to maintain a constant strain profile, an LSE could be constructed with no taper, greatly simplifying design (Pearson et al, 2005). Unfortunately, the trip along the cable would be quite lengthy, taking upwards of a month to traverse the distance between the surface and L1, so the elevator would only be used for cargo, with crew still riding on faster chemical rockets. Our proposed LSE design mirrors that proposed by Pearson et al.

There are two places to build an LSE, one through L1 and one through L2. The required cable length for an L1 LSE would be greatly reduced compared to an L2 LSE, due to the effect of the Earth's gravity. An L1 LSE would be easier to build and would be more easily reachable by craft from Earth orbit, whereas an L2 LSE could be used to launch interplanetary craft from the cable's tip and could service settlements and other infrastructure on the far side of the lunar surface. By the end of phase two an L1 LSE and an L2 LSE will be fully operational. There are two major configurations for the LSE, a typical tapered cable connected to a massive counterweight, or a balanced cable that tapers to a point and then continues on untapered for a great distance, with the mass of the untapered section replacing the counterweight. The latter configuration will be used for the L1 LSE and the former for the L2. The L1 LSE will consist of a tapered segment 25,000 km long connected then to a uniform segment 180,000 km long, the end of which would be able

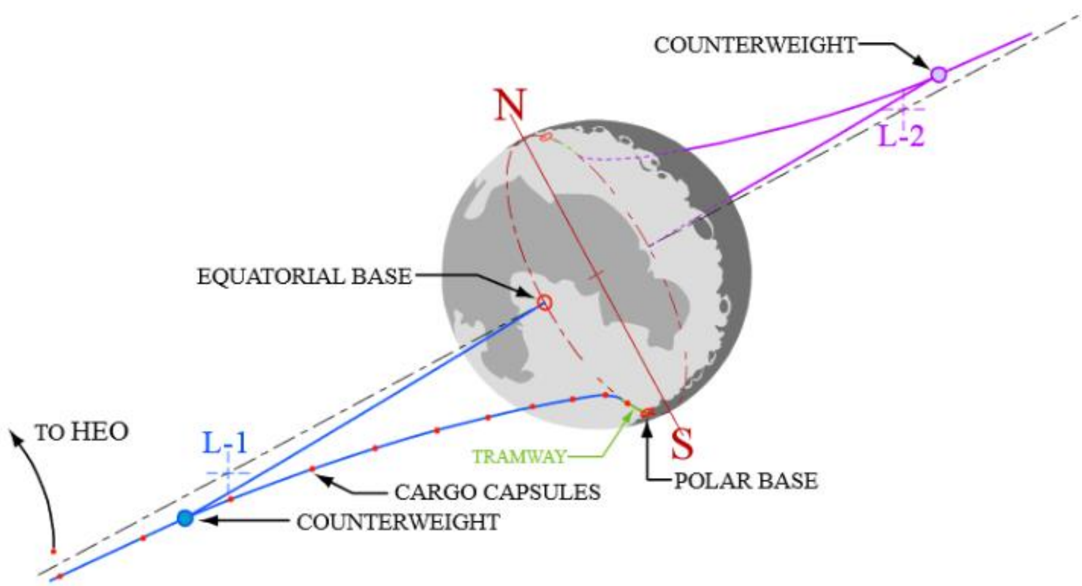


*Figure 15: Lunar space elevator (Pearson, 2005)*

to release payloads into and receive payloads from LEO. Along the length of the cable there would be small waystations from which maintenance and monitoring of the elevator will be carried out. The end of the cable will be anchored at the equator, as close as possible to the equatorial outpost, to assist in the easy transfer of cargo. The cable will actually be comprised of a number of ribbons of material, connected at intervals, to keep the structure intact if any single cable breaks. In the event of a breakage, the other cables would be able to take the load until that section could be repaired (Pearson et al, 2005). A multi-cable design would also serve to drastically increase the cargo throughput of the elevator.

The climbers will take the form of cargo canisters suspended on wire trusses and clamped to the cable by two pairs of wheels which will transport the climber up and down. Power for the climbers will come from large solar panels and lithium-ion batteries when the climbers are in shade, which due to the heights they are traversing, is only a small portion of the trip even during the new moon (Pearson et al, 2005).

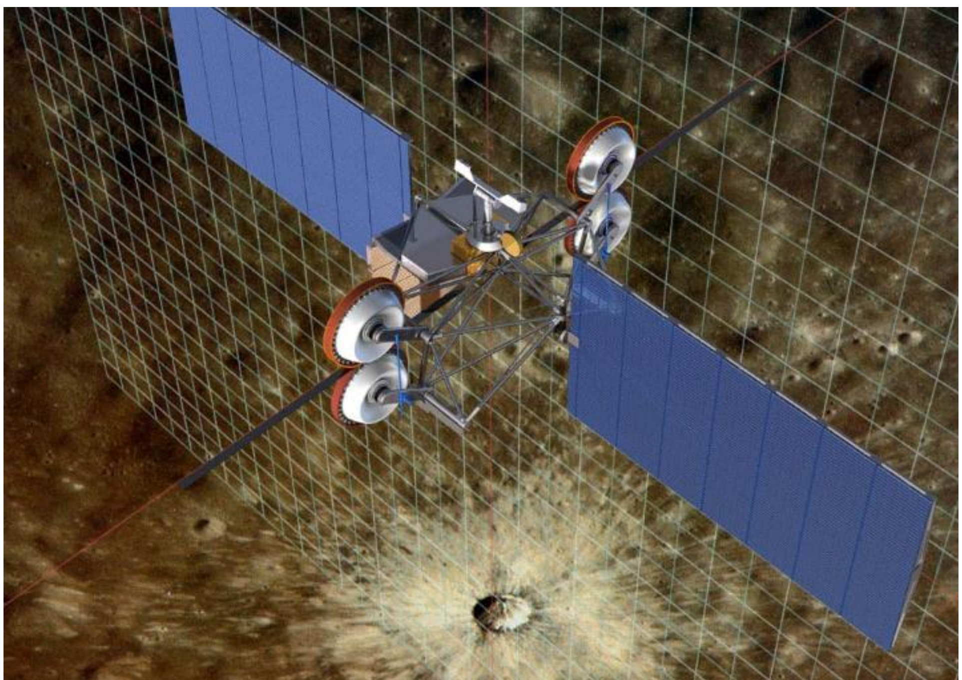

*Figure 16: Robotic Climber Concept (Pearson, 2005)*

Construction of the LSE will proceed as such: a fleet of orbital transfer vehicles (OTV), equipped with high efficiency propulsion systems such as ion engines or solar sails (Appendices B & C) will be launched into LEO and will carry cable sections, climbers, and other materials from LEO to L1 where they will be assembled and the cable deployed. After the first section of cable is anchored to the surface, it will begin to transfer supplies to the equatorial base, as well as cargo to facilitate the construction of the mining facilities, processing facilities, and maglev transportation system. Once the production facilities are functional and sufficient building materials can be produced, construction will begin on a "tramway" connecting an additional cable over land to the polar station. The "tramway" will consist of 1 km high towers spaced roughly 90 km apart from which the cable will hang (Pearson et al, 2005). About 30 of these towers will be required to reach the polar station. They will be wire structures constructed from the ground up using local metals.

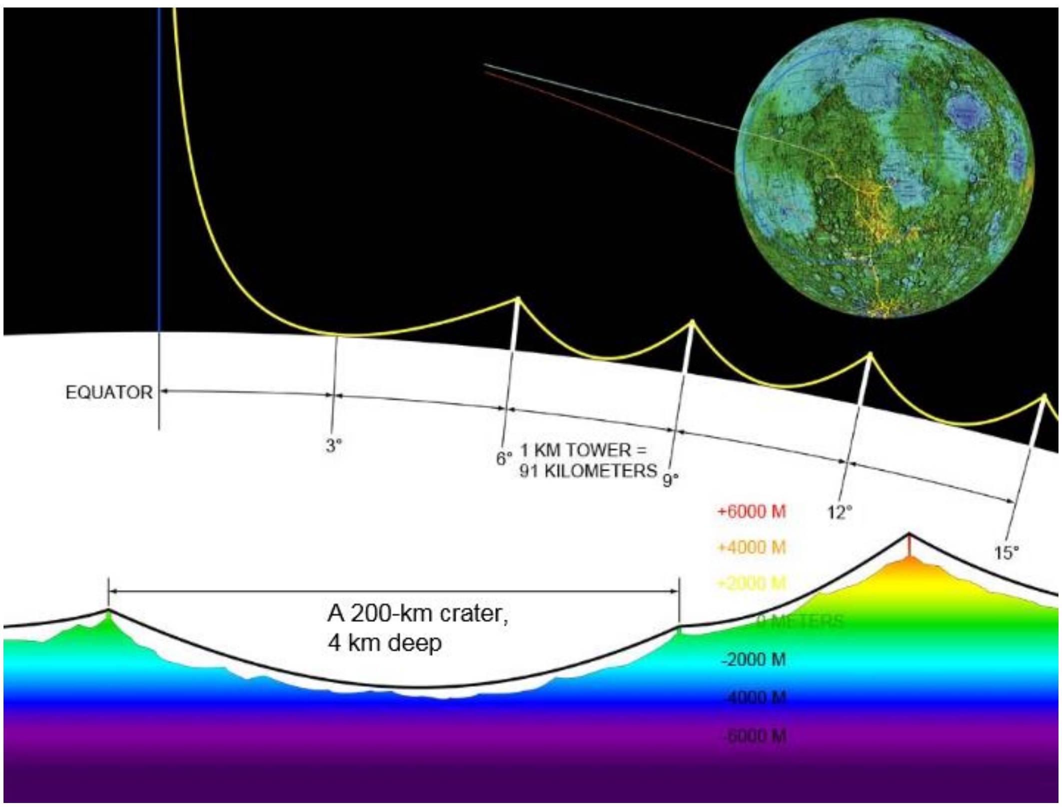


*Figure 17: Lunar Elevator and Tramway (Pearson, 2005)*

Due to their lightweight construction and low gravity the construction of these structures should be relatively simple. The initial construction phase, not including the tramway will take place early in Phase 2 so as to maximize its impact on the other construction efforts. After the first L1 LSE is up and running, a secondary L2 LSE will be constructed using the same techniques, to service the observatories and other facilities on the lunar far side.

Once completed, a fully operational LSE could transfer up to 500,000 tons of cargo between Earth orbit and the lunar surface per year, at a price per kilogram roughly equivalent to the price to put that same cargo into LEO (roughly $10,000 per kg at time of writing) (Pearson et al, 2005). The total cost of the project including development costs has been estimated to be on the order of $35 billion. Its construction would allow the infrastructure for Phase 2 to be built at a fraction of the cost and would allow transport of lunar materials into LEO to facilitate in space construction on an unprecedented scale. The fleet of OTVs that helped in the construction of the LSE will be repurposed to efficiently transfer cargo between the elevator and facilities in LEO where large scale in space construction can begin to take place to greatly augment human capabilities in space.

## Maglev Transportation System:

A magnetic levitation transit system will connect the Shackleton crater site to the equator, allowing convenient and efficient transportation of astronauts and supplies between the sites. A maglev system is ideal for the lunar surface because there is no atmosphere. On Earth, the majority of power used by maglevs is for overcoming drag, but without any drag, a lunar maglev would require little power. Maglev trains are the fastest form of ground transportation on Earth, but the lunar version could be faster, again because of the lack of drag. Assuming a speed of 600 km/h, a maglev car could travel the 2,700 km between the south pole and the equator in 4.5 hours. Because the cars do not contact the track, the ride is very smooth,

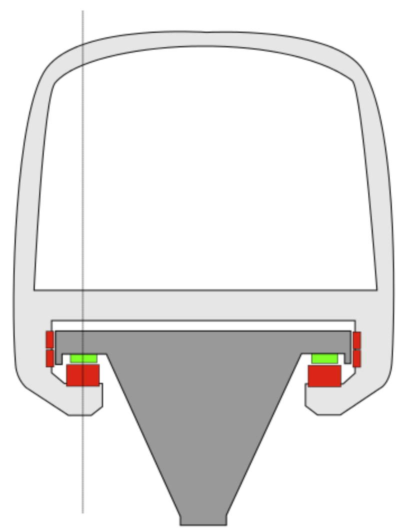

*Figure 18: Maglev rail and car cross-section (Stefan 024, 2007)*

allowing the transport of sensitive cargo. The lunar regolith contains nearly all of the materials needed to build the maglev track, so construction can be carried out robotically on the lunar surface.

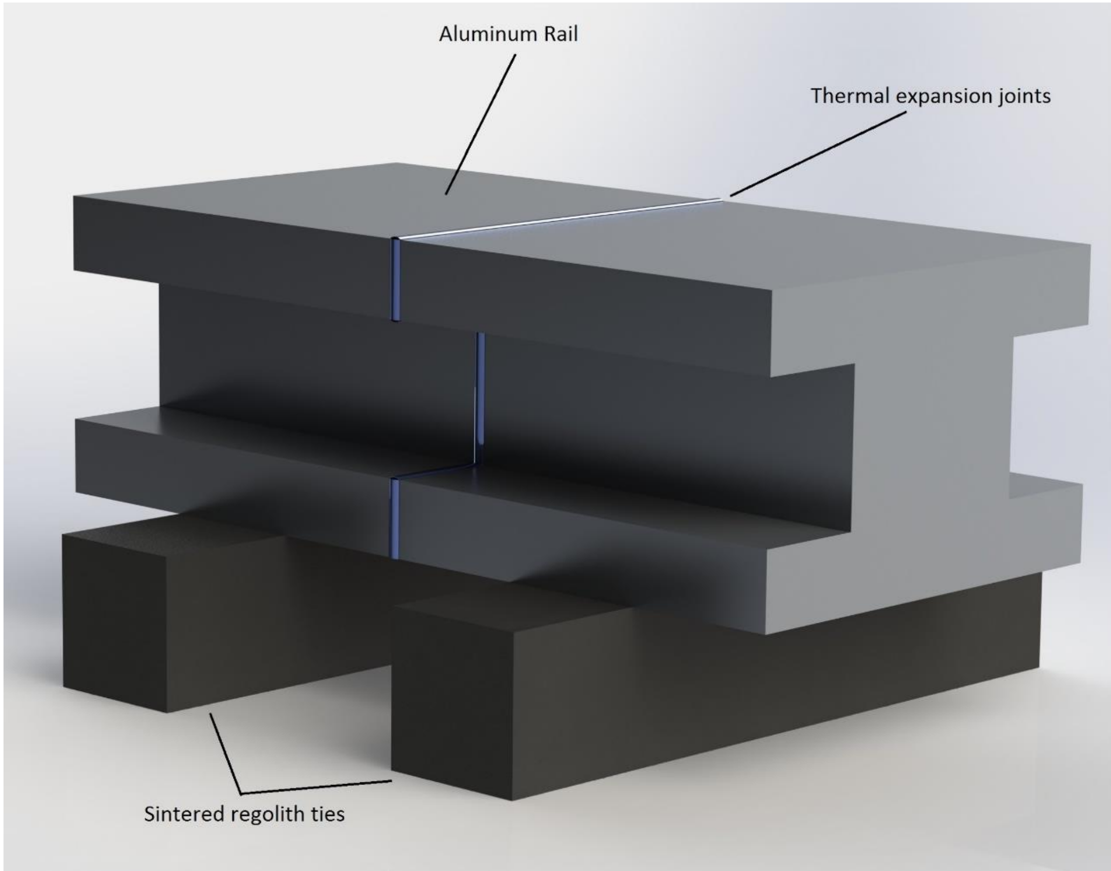


*Figure 19: Illustration of Maglev Rail*

The maglev track consists of a power-carrying aluminum rail supported by a series of ties made from sintered regolith. Solar panels will cover the rails to provide dedicated power for the system (Armstrong, Thomas, Bogen, Moore, & Reynolds, 1993). Two sets of tracks will be constructed to allow simultaneous travel in both directions. Pressurized cars will be used to transport astronauts, while cargo can be transported by unpressurized carriers.

Initial planning and surveys will be required to determine a relatively flat and straight path for the tracks. Straight tracks are necessary in order to reduce the centripetal accelerations experienced by passengers going around corners. These forces are proportional to the square of velocity around the corner and the reciprocal of the radius, so straight tracks allow higher speeds to be reached without endangering the passengers. Once a suitable path is found, construction will begin with robots that flatten out the lunar surface and use the regolith they displace to create sintered blocks. Then another type of robot will process the regolith for aluminum, which will be used to create the power-carrying rails. Lastly, a robot will travel along the completed sections of track, roll out the solar panels, and connect them to the rails. When the system is complete, cars can be delivered from Earth and begin travelling between the sites.

Two major issues that the maglev system faces are thermal expansion and power loss due to the length of the rails. The rail will be exposed to sunlight for the 2-week lunar day. During this time, they will absorb heat and expand. Multiple rails with gaps bridged by a flexible conductor will allow the rails to expand safely (Armstrong et al, 1993). Since the cars are suspended above the rails, these gaps will not cause any vibrations or discomfort for the passengers. From the formula for thermal expansion, we see that a 3 m aluminum rail exposed to a temperature increase of 320 °C (the equatorial temperature difference between day and night) will expand by about 2 cm.

$$\Delta L = L_0 \alpha \Delta T = 3\ m\ * 0.000023\ K^{-1} * 320\ K = 0.0221\ m$$

(The Engineering Toolbox, n.d.)

Therefore, adding a gap of 3 cm between every 3 m of rail (night length) should accommodate any conceivable thermal expansion.

Additionally, power will be lost due to the length of the rails. The placement of solar panels along the rails can overcome this power loss, but at night an alternate power source will be needed to provide enough power for the system to operate (Armstrong et al, 1993). If a reliable superconductor is discovered, it could be used to reduce the power consumption of the maglev system.

## Launch Pad:

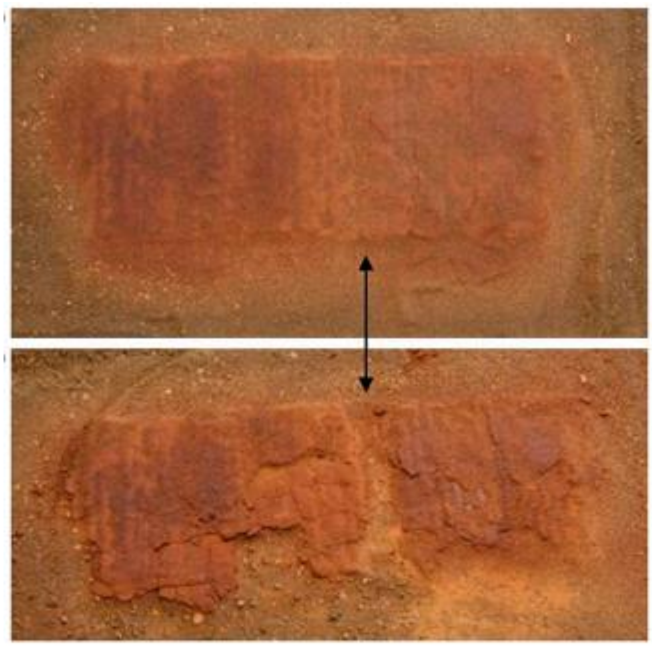

*Figure 20: Before (top) and after (bottom) view of sintered soil when exposed to rocket exhaust (Hintze & Quintana, 2013)*

A launch pad is a necessity for the equatorial base, as supplies and crew will need to be delivered frequently. Launching from and landing at the equator is far more efficient than at the poles as no orbital plane change is needed. A polar launch pad will also be needed, however. Landing and launching directly on the lunar surface kicks up dust, which can travel long distances at high speeds. Displaced dust can cause visibility issues (as seen in the Apollo missions) and can damage any infrastructure it comes in contact with (Hintze & Quintana, 2013). One method of creating a stable launch pad is sintering of the lunar regolith. By melting and hardening regolith in layers, a ceramic surface will be created that will prevent the spread of dust on launches and landings. Research has shown simulated lunar soil to possess a compressive strength similar to that of concrete after sintering (Cooper, 2008). The surface can be hardened using robots with a heat source (either microwaves or concentrated sunlight). Additionally, placing the launch pad in a small crater would help keep any ejected dust contained within the crater rim. A nearby crater will be considered in the choice of site for the equatorial base, but if one does not exist, a wall of regolith with a sintered outer layer could be built around the launch area. The maglev system will extend to the launch site so that materials and astronauts can quickly reach the equatorial outpost.

## Far Side Telescope:

A lunar observatory will be established on the far side of the moon in order to detect Near Earth Objects that could pose disastrous threats to the Earth. This part of the colony will also serve as a large attraction for researchers due to the innumerable benefits of lunar based astronomy (further elaborated on in Appendix D). The first telescope placed at this site will be an optical telescope. Later, x-ray, gamma ray, radio, and infrared telescopes will be constructed as part of a large lunar observatory that will take advantage of the many benefits of lunar based observation. The optical telescope will consist of a parabolic mirror coated in aluminum and made primarily of lunar regolith mixed with epoxy. This type of telescope is extremely cost effective and is designed such that it benefits from the lunar environment in its construction. First, the shape for the mirror will be made by creating the base out of epoxy and then spinning it. As this hardens, the forces on it from the spinning will cause it to form the parabolic shape. Then, the process by which it is plated relies on the lunar vacuum. The rest of the telescope is constructed from lunar materials making the shipment of parts cheap and its construction straightforward.

## Food Production:

At the beginning of phase 2, earth supplied food will begin to be phased out as food production begins to take its place. A trade study using SWOT Charts (shown below) has been used to decide the

*Figure 21: Automated food production facility*

type of farming that will take place in the permanent settlement starting in this phase of the mission, and continuing on into phase two. By this method, it was decided that the most efficient method

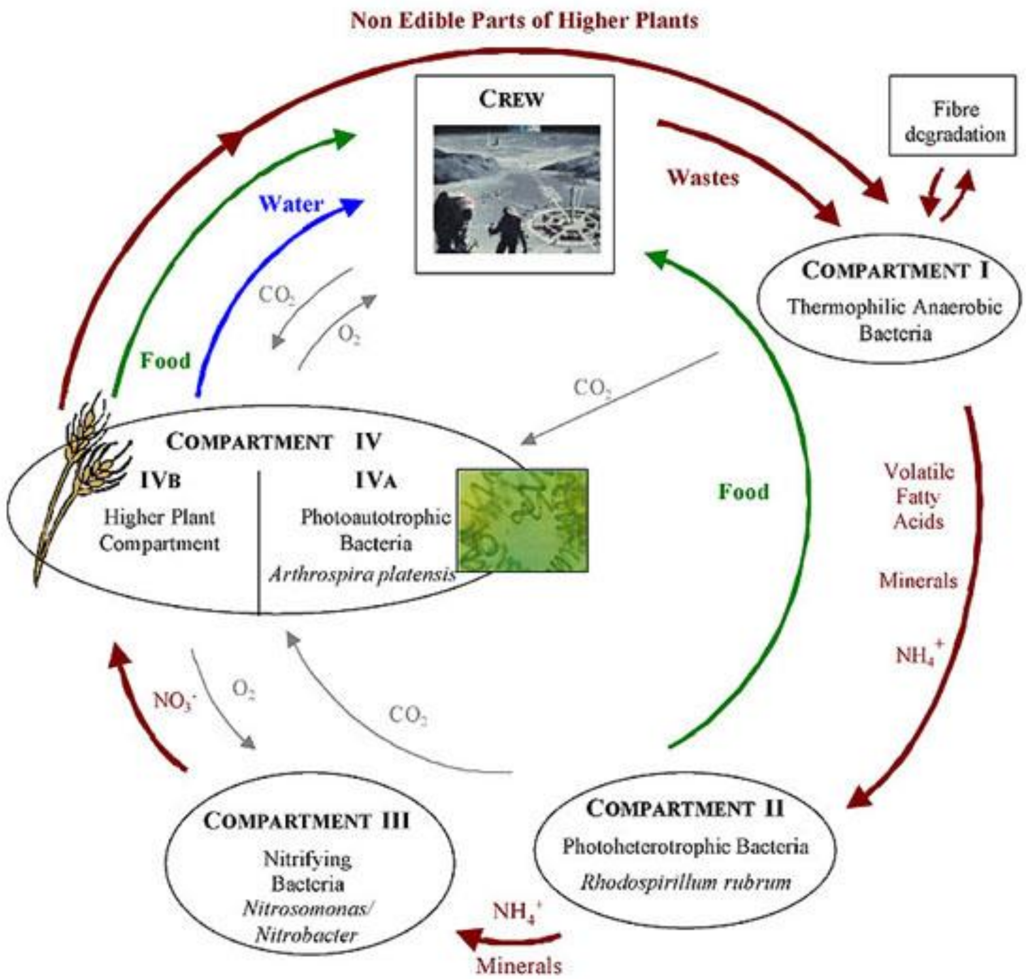


*Figure 22: Diagram of MELISSA System (ESA, 2009)*

would be to use aeroponics which may provide a superior crop yield along with lower water usage. This system will also be integral to the life support system which will filter the CO2 into the agricultural sectors of the settlement.

**Geoponics**

| Strengths: | Weaknesses: |
|---|---|
| • Traditional method of growing crops, greatest body of research available | • Soil will cost much more to ship |
| **Opportunities:** | **Threats:**<br>• Not considered to be as clean as other methods leading to more disease |

**Hydroponics**

| Strengths: | Weaknesses: |
|---|---|
| • Very little or no soil is needed for plant growth<br>• Reduces the land needed to cultivate crops<br>• Reduces amount of water used<br>• Slightly cheaper than aeroponics | • Nutrients need to be constantly replaced.<br>• Will require more water than other growth methods |
| **Opportunities:**<br>• Plants tend to thrive more in this type of system than in geoponic systems, leading to a larger crop yield | **Threats:**<br>• Has been shown to lead to more diseases than aeroponics |

**Aeroponics (selected for use)**

| Strengths: | Weaknesses: |
|---|---|
| • Eliminates the need for soil<br>• Nearly does away with having to use water<br>• Minimizes the area needed to grow crops<br>• Cleaner than other types of growth methods | • Slightly more expensive than hydroponics |
| **Opportunities:**<br>• Reduce water usage<br>• Plants tend to thrive more in this type of system than in geoponic and hydroponic systems, leading to a larger crop yield | **Threats:**<br>• If the equipment to maintain the plants malfunctions the roots will rapidly dry up |

*Figure 23: Study of plant growth methods*

## Schedule:

Phase 2 will proceed over three periods of time and is estimated to last around 10 years. Period A will be carried out as follows. First the equatorial shelters shall be set up. Next, basic launch pads will be constructed at both the equatorial and polar sites. Small scale mining and processing operations will begin at this time. The future path for the maglev rail track will be determined and cleared to a certain degree, as will the site of the future observatory. These tasks are estimated to take approximately 1 year. Period B will then commence. First, the initial space elevator will be constructed with the cable reaching as close to the equatorial base as possible. Using cargo delivered by the space elevator, construction inside of the lava tube will begin. Excavation and habitat expansion will commence at the polar base at the same time. At this time, construction will begin on the maglev rail system and the observatory. Period B is estimated to take 4 years to complete. Period C will then begin with the conversion of excavated space into habitat space. Food growth systems will then be installed and large scale food growth will begin at this time. Next the space elevator “Tramway” will be constructed to directly connect the polar outpost to the space elevator. Equatorial construction and polar excavation will continue to be expanded throughout this period as needed. Later on in this period, the food growth systems will be expanded to better approach true sustainability. Near the end of this period the maglev rail system and the observatory will begin operation. Period C should last roughly 5 years. Throughout Phase 2, the power, mining, and processing systems will be expanded as necessary to meet the settlements’ growing demands.

## Gantt chart for phase two

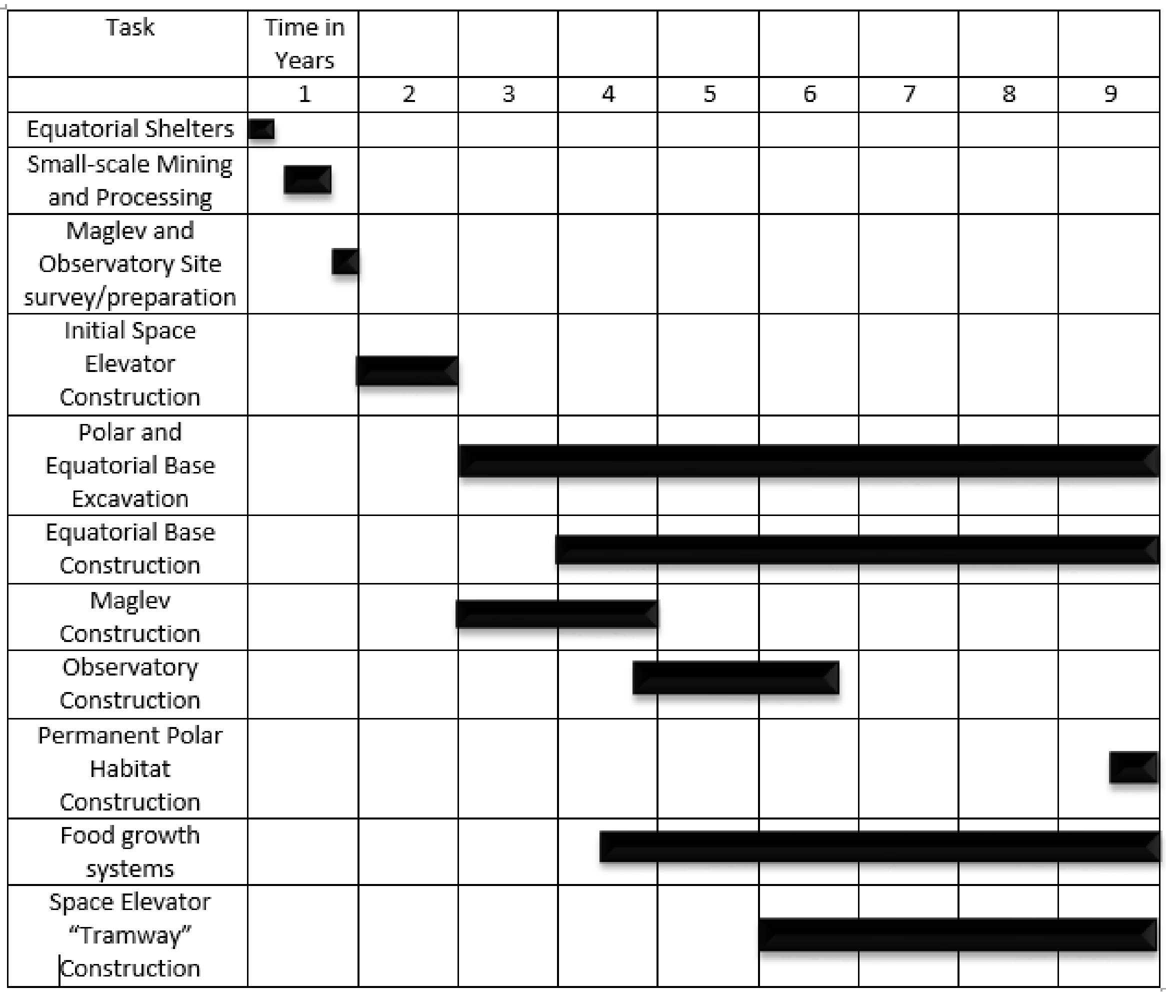


*Figure 24: Gantt Chart of Phase 2 Schedule*

# Phase 3: Lunar Colony

## Goals:

Phase 3 of the lunar colony will be an ongoing effort without a well-defined end point. It will mainly revolve around the largest permanent structure being completed at the Shackleton Crater and filling the newly created habitats and carrying out a number of tasks on the lunar surface and beyond. The population goal for this phase will be to expand to 10,000 inhabitants within 10 years. In order to complete this task, the existing facilities and infrastructure will be expanded and new settlements formed as needed to house the new population. In addition, by the end of those ten years, the lunar colony should be almost entirely self-sufficient, cutting necessary cargo from Earth to a minimum. Such a large population increase will also necessitate new terrestrial policies on lunar resource usage and a lunar “society” will have to be developed.

## Spaceport:

At the commencement of Phase 3, the necessary production facilities will be in place that rockets can be constructed entirely from lunar materials minus some specialized parts that would be shipped from Earth. Manufacturing could either take place on the lunar surface, in lunar orbit, or at stations connected at L1 and L2 to either of the space elevators that will be in full operation by this point. Part of the spaceport system would be a robust launch platform to ferry crew between the surface and orbit, as the space elevator climbers move far too slowly to transfer passengers. This launch platform would be constructed from lunar materials wherever possible and would be able to accommodate multiple takeoffs and landings per day and to refuel any vehicle that lands there, to maximize reusability. This primary platform would be located near the equatorial base to maximize the efficiency of incoming and outgoing spacecraft, but a secondary platform would also exist at the polar base to directly service spacecraft landing there. Additionally, any craft released from the counterweight of the far-side space elevator would be released on an interplanetary trajectory without the use of any propellant. A large interplanetary ship could be constructed in pieces on the lunar surface, shipped up to the counterweight and assembled there, to be launched on an interplanetary trajectory. Such a system could extend humanity's presence in the solar system by leaps and bounds.

## Structure Development:

The main expansion in phase three will be centered on either the creation of a man-made tunnel or the excavation of a lava tube that will connect to the rim of the Shackleton crater. This will house large communities with everything needed for a society to permanently establish itself on the moon. This phase will include 4 basic steps:

1. Locating a lava tube or spot to begin excavation
2. Building the main supports and structures of the location with the main port at the crater and several escape hatches to the surface
3. Establish housing and communities including food growth facilities and commence exodus to the moon of the general population
4. Construct smaller stations as needed around the moon

At the polar settlement, more excavations will be performed at different places along the sides of the Shackleton Crater, as well as any other suitable craters nearby. Long-term, a rail system could be put in place around the inner rim of Shackleton to simulate 1G and help combat the bone and muscle degeneration that the colonists will face. At other places on the surface, other lava tubes will be settled in, in the same manner as the ones in phase 2 and 3. Each new settlement would be connected to the others via the maglev rail system for easy transit of cargo and passengers. Another major site that settlements could form would be in the northern polar region, and their structure would mimic that of the southern polar settlements: constructed into the inner walls of large craters. Other, more specialized outposts, for research or mining purposes will also be constructed, as needed. The processing and manufacturing facilities for ISRU will be moved to areas away from the Shackleton crater in order to free up more space for settlements, and to allow the facilities to expand. They will be moved to locations surveyed during the previous phase, tentatively sheltered in lava tubes or pits, and will grow substantially in size to bring the colony as close to self-sufficiency as possible.

Settlements would be constructed to be completely modular. Underground area would be excavated and sealed, and then could be used for whatever purpose the colonists desired. Larger settlements will have large residential areas as well as food production, research, manufacturing, and recreational “districts”. Smaller outposts such as those that might exist at the far side observatory would likely only have residential, research, and small food production areas, due to their small population and specialized nature.

## Food Production:

Food production will use the same automated aeroponics system from phase 2. However, this will be on a larger scale and will consist of an underground module to start off, along with modules located in above-ground domes constructed after the initial underground colony is finished. The aboveground domes will provide natural sunlight for growth, and the underground areas will begin producing a backup supply of food. In addition, a 3 month emergency supply would be stocked that would be large enough to support the population.  In vitro meat production will be researched and implemented to provide an alternative to plants for residents.

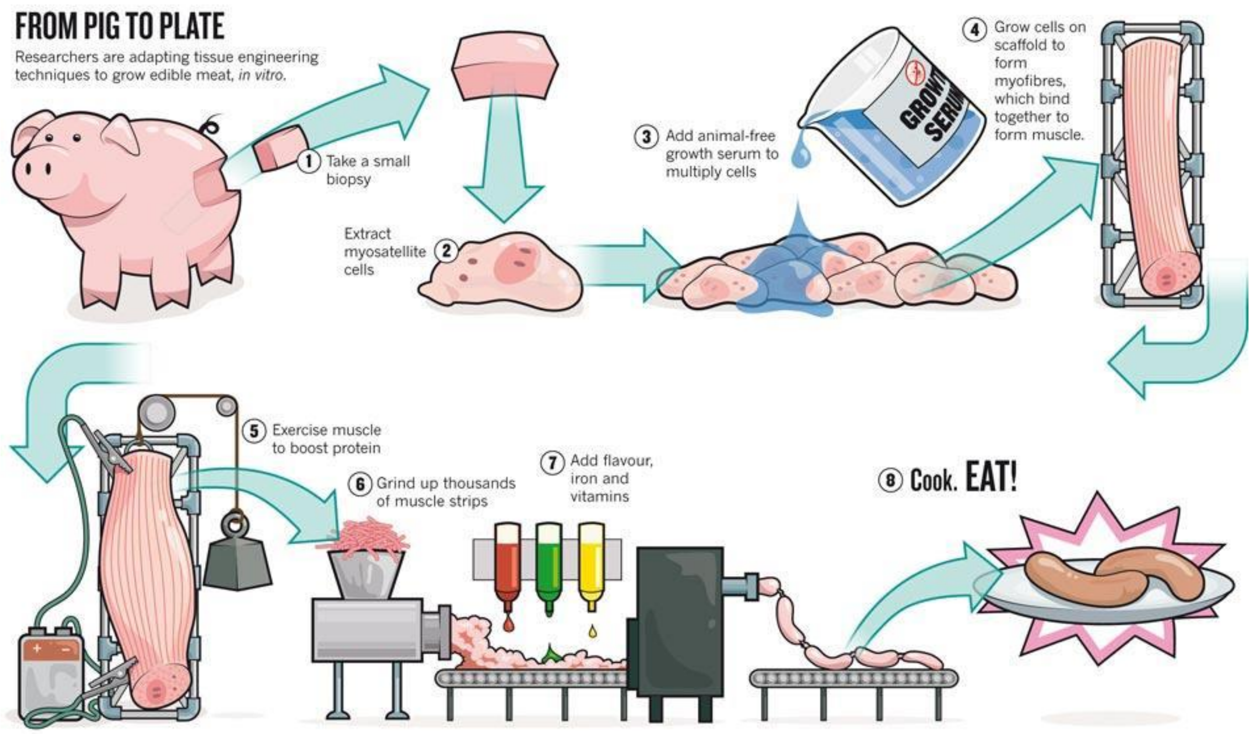


*Figure 25: In vitro meat production (Spencer, 2010)*

## Radiation Shielding:

The underground structure will have its own natural radiation protection from the thick layer of regolith between it and the outside environment. However, the outside domes will need further protection. Areas that do not need views of the outside or sunlight to come in will be covered in a thick layer of regolith. Leaded glass will be used for areas that cannot be covered in regolith. Research will be performed to determine the feasibility and effectiveness of generating a local magnetic field around individual outposts and settlements to simulate the protection of Earth's magnetosphere. If successful, this technique will be employed across the entire settlement and at the outposts.

## Mitigation of Gravitational Effects:

Preliminary research conducted in phase one will be used to tweak the initial plans for this phase. As is standard, all inhabitants will have mandatory exercise which will be a part of a program deemed appropriate for their age group. Supplements will also be researched, and if beneficial in phases 1 and 2, will be provided to the colonists. While these may help with the mitigation of the effects caused by gravity that is approximately ⅙ that of earth, it cannot fully replace time spent in 1G. For this reason, a 1G simulation train will be built on the perimeter of the crater that will travel in a circle fast enough to generate an outward force from the spin that will match the gravitational force of that on earth. Gravitational effects on health and mitigation of lower Gs is further expanded on in Appendix H.

## Population Control:

The population target for the end of Phase 3 is 10,000 people. This would mean adding about 9,700 people over a period of 10 years. In order to accomplish this goal, about 21 people will need to be added to the colony every week. Transportation would be accomplished by launching the colonists into low earth orbit, where they are picked up by a shuttle and transported to specialized craft in lunar orbit that will transfer them to the surface. If research conducted in Phases 1 and 2 indicates that human embryos can safely develop and grow in the lunar environment, some of the population growth may arise from lunar births, lessening the number of people to be transported from Earth. In order to support the large population, hospitals will be constructed at the equatorial and polar settlements, and they will be adequately staffed by doctors, nurses, and support personnel among the arriving colonists. A wide variety of occupations will be available for the colonists. These occupations include but are not limited to scientists, engineers, medical personnel, food growers, administrative personnel, maglev and space elevator operators, maintenance personnel, mining personnel, and workers in the rocket production facility.

## Tourism:

In addition to permanent colonists, people may visit the moon temporarily by staying in lunar hotels. Lunar tourism will generate further interest in the colony, allow unsure settlers a chance to experience the moon without making a permanent move, and create additional revenue for the colony. The hotels will be built alongside the permanent habitat space at the existing settlements, allowing them to utilize infrastructure that is already present. While the simple idea of vacationing on the moon may draw some tourists, attractions will be created to increase the accessibility of the lunar colony.

Due to the proximity of the equatorial site to the Apollo 11 landing site, one of the tourist attractions will be a lunar history museum at the site. The museum will be built around the remaining base of the lander and will feature the flag, experiments, and footprints left behind by the first astronauts preserved in their original state. Additional exhibits will present the history of lunar exploration including the theories and observations of classical astronomers, unmanned probes, the Apollo missions, and the planning and construction of the lunar colony.

Guided moonwalks would also serve as an attraction for guests. Guests would don spacesuits and experience the lunar environment in the same manner as the Apollo astronauts. Lunar rover tours of local features would also be offered to guests. During the lunar nighttime, these attractions would be replaced by stargazing. Without atmospheric interference and light pollution, the number of visible objects is much greater and nebulae and planets can be seen more clearly than on Earth.

Indoor sports arenas would serve as another attraction while also providing guests with needed exercise. Conventional sports such as soccer and basketball would be vastly different due to the lunar gravity, and would have a much greater vertical aspect due to the ability of players to jump higher and remain off the ground longer. This could also lead to the creation of new sports that can only be played in the lunar gravity.

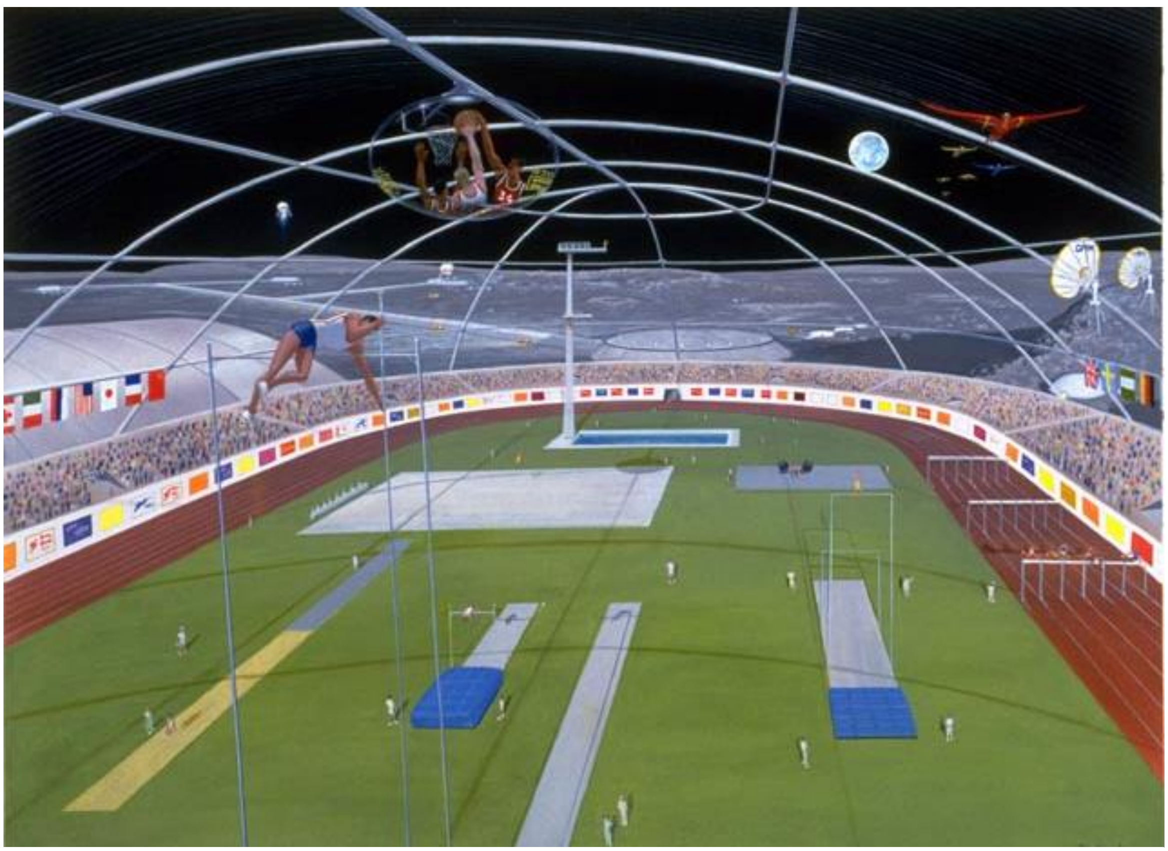

*Figure 26: Indoor sports arena concept (Rawlings, 1995)*

## Power Systems:

The power systems will be expanded in the order of hundreds of megawatts in accordance with the needs of the colony. Tentatively, the capacity of the solar power plant can be increased to 500 MWe covering an area of 190,000 square km, by increasing the number of arrays. However, solar cells with greater efficiency can be developed to cut down on this area. Technologies such as quantum dots that are currently in design phase but have the potential to increase efficiency by up to 66% could be considered (Nozik, p. 1). The number of Space Molten Salt reactors (SMSR) will also be increased, and other designs such as the advanced heavy water moderated thorium reactor (Subramanian, 2003) could be considered, or the previously considered SP-100 or HOMER-25 reactors could be remodeled to use thorium. Use of local thorium to power the nuclear reactors will also decrease the cost of fuel. When the research has advanced enough, Helium-3 nuclear fusion reaction can tentatively begin to replace the SMSRs due to the lower radioactivity risks and greater power yield of the Helium-3 fuel cycle (Appendix A). Early in Phase 3, test studies will be carried out to prove commercial viability of large-scale microwave transmission of solar power to Earth, and for large-scale Helium-3 nuclear fusion to provide power for local and terrestrial use.

## Dust Mitigation:

The effects of lunar dust can seriously harm the power systems and electrical components that are installed on the lunar surface without cover. Larger surfaces, such as the solar arrays, maglev train, and telescope will be covered in two coatings - Tungsten Carbide which will repel dust when an electrical current is passed through it, and Aluminum Oxide which prevents damage from the dust. The repulsion will require high voltage power so it will be used for more susceptible surfaces. For smaller equipment, maintenance stations at the main colony and outposts will be capable of using acoustic levitation to lift the dust away and then blow it off with a burst of compressed air (Bardi, 2015). In later stages, when higher power efficiency is achieved and methods of dust repulsion are improved based on Phase 1 and 2 research, such coatings may be used on a large-scale.

## Political Implications:

As the first country to successfully complete a manned lunar mission, the United States has historically had a significant lead in the space race. In recent times, however, lack of political backing has delayed proposed manned lunar missions (Hickman, 2012). In the meantime, other countries have announced plans to establish moon bases more overtly. China has sent unmanned missions including the Chang'e orbiters, which charted the mineral distribution on the moon and the lunar regolith depth, as well as a lander and rover (Simko & Gray, 2014). Aside from a manned lunar mission planned for 2020, the China National Space Administration has plans to build a "base on the moon as we did in the South Pole and the North Pole."

In addition to China, Japan, Russia, India, Korea and the European Space Agency (ESA) have also deployed orbiters to study and observe the lunar surface. The Russian Space Agency (RSA) and Indian Space Research Organization (ISRO) also launched a collaborative project, which used an Indian supplied rover and orbiter and a Russian lander to study the regolith. The RSA has planned manned missions for 2030 with a lunar base in the future, while Korea and the ESA have plans for 2023 and 2018 respectively. This degree of international interest in exploring the moon's helium-3 resources, especially from countries with comparatively new space programs, has precipitated in a second race for the moon. This could potentially create sociopolitical and diplomatic complications. The first country to establish a base on the moon will certainly have the chance to monopolize the mining of lunar resources, most importantly helium-3. As a leading scientist of the China National Space Administration has said, “whoever first conquers the moon will benefit first" (Lasker, 2006).

At present, no one possesses a military force that could operate in space to challenge another state’s claims to the moon. In addition, for helium-3 to become a global power source lunar helium-3 mining, extraction and transportation will need to reach a large enough scale to support global energy needs. More significantly, Helium-3 nuclear fusion reactors must first become commercially viable and globally widespread. This would enable a large number of countries to generate power from Helium-3. Until these two steps can be accomplished, a monopoly of lunar Helium-3 resources could be unavoidable. Even if it were shared between major developed powers, it would lead to great disparity between developed and underdeveloped countries, forcing the latter states to completely rely on the former for energy. Such a monopoly or disparity will inevitably pose a great diplomatic obstacle in the future, one resolvable only by joint international cooperation efforts.

## International Collaboration:

In order to establish a permanent colony, international cooperation between space-faring nations will be highly desirable. Realistically, an undertaking of this scale cannot be accomplished alone by any spacefaring nation under the current circumstances. The involvement of multiple countries across the globe, especially those with advanced space programs will directly benefit the venture in many ways. If the countries with existing space programs made available their launch sites, it would allow for a large number and variety of global launch sites. If the countries hosting the launch sites entered an agreement whereby they could subsidize the launch costs, it could greatly reduce the overall cost of the program. Therefore, it will allow for greater launch flexibility, not only with regard to location but also costs. In addition, a schedule permitting multiple launches will also cut down the time required for the construction, maintenance and servicing of the colony. Since many of the concepts involved in the creation of this base are still in design phase, it will realistically take a great deal of time for these designs to reach a higher level of technological readiness. Although it will come with political caveats, the division of financial and technological resources and tasks between participating countries, and the sharing of research within the international scientific community has the potential to substantially reduce the time required for designs to reach higher levels of technological readiness. However, before any level of international cooperation can occur, a comprehensive agreement between space-faring and non-space faring nations is required to ensure and safeguard the resources and sovereignty of all countries involved, and to prevent any conflict.

Although the Outer Space Treaty of 1967 declared the moon to be under international control (Dobransky, 2013), none of the countries that currently have major space programs are signatories of the Moon Treaty. Most significantly, this treaty was vetoed by the two major space powers in 1967, Russia and the United States. The concept of international control and some of the specific terms of the treaty are conscientious. By declaring the moon the shared heritage of mankind, the treaty bans the mining and utilization of the moon’s resources by any party, and the act of claiming any part of the moon. It is also possible for the signatories to withdraw from this treaty after giving only a single year’s notification (Hickman, 2012). Given the current political situation, the first country that can establish a colony with the view of tapping into the moon’s resources of rare-earth metals and power in the future may have the chance to establish a monopoly over these resources, and over parts of the moon. Therefore, a new and comprehensive Moon Treaty will have to be drawn up to lay down guidelines of how the moon will be shared, and to foster international cooperation.

## Moon Treaty:

The new Moon treaty will allow each nation to extract and utilize lunar resources to fulfil their needs, but within reason. Quota systems will be used to ensure reasonable sharing of resources. It will also prevent any country or corporate entity from laying claim to any part of the moon, which will be accomplished in two ways. Firstly, by using deterrents to prevent the militarization and weaponization of the moon. All party nations will agree to ban such activities, with any breach leading to economic and diplomatic sanctions. A similar treaty banning militarization should be ratified by all members of the United Nations Organization to prevent countries that are not party to the Moon treaty from partaking in such activities.

Secondly, conflict will be discouraged by using the colony as a tool to foster international cooperation. The lunar colony will be a truly global enterprise. The living quarters of the permanent residents will be divided in a way to create diverse micro communities within the greater community. Following the model of the International Space Station, each country will have ownership and responsibility for an element of the permanent settlement, and the initial crews and later permanent inhabitants will comprise nationals of all signatories. The national space agencies of all signatory countries will cooperate on the operation and management of all lunar facilities and earth-based support. To specifically prevent the monopolization of lunar power resources, a provision will be added for the reasonable sharing of Helium-3 resources for terrestrial use during the later phases. If microwave transmission of lunar power to meet terrestrial power demands becomes a reality, the treaty will be amended to foster reasonable sharing of the cost and use of the generated power.

An International Space Council will be impaneled to oversee this effort. The Council will consist of representatives from each of the party nations' Space Agencies, diplomats and representatives of any corporate entities partaking in the venture. It will fall under the legal jurisdiction of the United Nations Organization, who will ensure there are no breaches of the Moon Treaty. Each country's national agencies and any commercial entities belonging to that country will operate within that country's law. Any conflicts between the laws of countries will be resolved by the International Court/United Nations.

## Law and Order:

In addition to political cooperation, the permanent presence of a large number of humans on the moon will also require a constitutional system. The International Space Council will agree to a common set of laws that will safeguard basic human rights outlined by the UN Charter of Human Rights. This will evolve as the number of parties and inhabitants grows. It will serve to preserve law and order at the base, protect the rights of inhabitants and intellectual property rights, as well as setting down liability laws. All parties involved in the colony will sign a cross waiver of liability preventing them from holding each other liable for damages except under special circumstances. Legal jurisdiction for breaches of the treaty will fall under the United Nations and the International Criminal Court, which will ensure that due process is followed to reduce conflict between international partners. All residents will also be subject to a Code of Conduct that will regulate their behavior. A small judicial council empaneled by judges belonging to each of the collaborating nations will handle petty crimes, whereas crimes of a more serious nature will be referred to the International Criminal Court. A police force modeled on the United Nations police force comprising individuals from all collaborating nations will maintain law and order.

## Health:

In the past, space travel has been limited only to those who have superior physical and psychological health. In the future, it is possible that space will become more accessible to the general population. Also, with this plan it is assumed that many births will happen in space. As such, extensive consideration must be made in order to support the average person in the grueling environment of space. Even if at the time of the implementation of this project, humans still only decide to send the fittest people into space, the psychological ramifications could be enormous and therefore must be taken into account so that conditions can be amicable for all peoples.

This design takes that into account in several ways. A rotating crew is suggested at the beginning in order to mitigate the effects that we would not yet have infrastructure in place to resolve. External views in the form of windows will be provided in temporary and permanent facilities to provide natural sunlight. It is suggested that in later phases, psychologists, psychiatrists, and perhaps even cultural anthropologists will be part of the crew in order to maintain the health of the general population and gather valuable data. In the permanent structures, large open green spaces will be put into place along with community centers, means of education, and entertainment.

There will be a full service hospital with medical equipment specifically designed for use in the colony, and a number of smaller sized clinics, each of which will service some modules of the permanent residence. All residents will undergo regular medical exams, including mental health evaluations to ensure their mental and physical wellbeing. A part of the hospital will be a quarantine zone where patients with contagious or unknown conditions can be confined to protect the rest of the community. In extreme cases, an emergency vehicle will be used to transfer patients to the earth. Medical specialists may also be summoned from the earth for rare procedures.

As stated in other sections, the effects of lower gravity will also be of great concern and are discussed in depth in Appendix H. Suggestions for mitigating this have included the gravity train built in phase 3 around the rim of the Shackleton Crater, testing the effectiveness of supplements and using them if acceptable, and using personalized exercise and nutrition plans for each inhabitant.

## Lunar Environment:

For the colony to achieve self-sustainability and fully utilize the benefits to be garnered from the moon, the mining and processing of lunar resources is an imperative operation. As beneficial as it may be, however, such operations can potentially cause a lot of damage to the lunar environment by altering the landscape. Since no one has mined the moon, it is not possible to fully gauge the effects this could have. To avoid this, studies will be carried out during pilot ISRU operations to ensure mining operations are not harming the environment of the moon, especially relative to earth. The lunar tourism industry may also be impacted if the lunar environment was severely disfigured. The ISA must therefore develop and strictly enforce good mining practices specific to lunar mining conditions. Since the lunar resources are nonrenewable, good mining practices are also needed to ensure sustainability.

## Commercial Ventures:

There are many arguments for allowing greater freedom to corporations willing to invest in space commercialization. Commercial ventures can fill gaps in government funding, and private research can provide new ideas and perspectives. Currently, half a dozen corporations are working on Solar Power Satellite systems (Detailed in Appendix A), a program which NASA had to give up on due to lack of funding. In the future, they could spur a revolution in space based solar power technology. There is ample reason for increasing the role of corporations from simply acting as suppliers contracted by government agencies to leading the commercialization of space.

Admittedly, accidents such as the crash of Virgin Galactic's SpaceShipTwo last year, which resulted in a fatality (Witz, 2014) could raise some questions about giving corporations free reign to commercialize space. To counter such problems, comprehensive legal framework must be developed to regulate commercial activity, and ensure that checks and balances are in place and safety standards are strictly enforced. It is important, however, that this framework allows corporations the freedom to venture into space, to take initiative and innovate, and capitalize on the economic opportunities arising from the lunar colony and beyond. To encourage corporate spending in the early stages, the national governments could offer incentives such as tax benefits as they do on earth. However, once corporations get a foothold on the lunar colony and investments in a booming space tourism industry start to pay dividend, corporations may play an even bigger role than national agencies. The commercialization of the moon will have to be steadily carried out over time, as the economic viability of such ventures must first be proven.  Whether the future of space commercialization belongs to agencies like NASA or corporations like Virgin Galactic, both parties will be key in proving the economic viability and gleaning the benefits of a permanent lunar colony.

## Avenues of Research:

The lunar environment presents a unique opportunity for research in a multitude of different fields. A large percentage of the final population will be made up of scientists and researchers to take advantage of these opportunities. As stated previously, extensive research will be carried out on the long term effects of low-g environments on human health and development, as well as the viability of procreation in a sub-1G environment. A related avenue of research is that of genetic engineering of humans and other organisms to better survive in hostile environments such as the moon or Mars. It is theoretically possible in the future of the colony, though the subject is quite controversial and the ethics of its research and application are beyond the scope of this project. In addition to the field of biology, significant geological research will also take place. Once the necessary equipment and manpower is in place, a thorough geological survey of the moon will be carried out, to help us better understand its structure, history, and formation. In addition, the lunar gravity environment could potentially allow chemical or industrial processes that would be impossible on Earth, so a significant amount of research will be directed towards these areas of study.

## Suggestions for future IQPs:

Moving forward further into the future, a number of efforts could be undertaken to expand or enhance the colony that are outside the scope of this project. One such endeavor would be a large hotel in lunar orbit, whose design and construction would bring with it a number of challenges, but would significantly bolster tourism within cislunar space. Additional research could also be conducted to study the viability of transferring solar energy to the Earth in the form of microwaves, as well as Helium-3 nuclear fusion. The viability of capturing a comet or icy asteroid and placing it in lunar orbit should also be taken into consideration. Such a comet or asteroid would serve to solve whatever water issues remain within the colony. Finally, the possibility of protecting a large area of the lunar surface with a very strong magnetic field should be examined, so as to greatly expand the flexibility of human settlement on the lunar surface.

The next step in settling the solar system is a colony on Mars. A Mars colony would allow for the survival of humanity in the case of a catastrophic event such as a large asteroid impact in the Earth-Moon system. While much of the technology discussed in this paper could be applied to a Mars settlement, this settlement would face a very different set of challenges (for example, travel times on the order of months instead of days). An initial Martian settlement could be developed using a process similar to the lunar colony in this paper, but a future project could also examine the feasibility of a much larger settlement on Mars, including terraforming and/or other major operations to create and environment suitable for human life.

## Conclusion

There are those who believe that the moon holds nothing more for us, that there is no reason to return, and that all of our efforts should be focused on human colonization of Mars, or that humanity has no future in space at all. It is the belief of the authors that the moon is the currently best option to supplement further expansion into the solar system, and that doing so will prove beneficial to society. There are a number of untested technologies, and a great many more hazards that must be overcome before we can even think of colonizing another planet, and the moon provides a perfect test bench for both. The moon's bountiful resources would also be a boon, both for human exploration and for life on Earth. Furthermore, a lunar spaceport and rocket construction facility would greatly reduce the cost of conducting interplanetary missions, making the possibility of further expansion into the solar system a reality.

The challenges that a lunar colony would face are the same as those faced on Mars: namely the lower gravity environment, solar radiation, and pervasive abrasive dust. The moon is in some ways a more hostile environment than Mars, but is also much more accessible, meaning that if something goes wrong, it does not automatically spell doom for the crew. Because of this, the moon is an ideal place to test the technologies that would allow colonists to overcome the many challenges that they would face.

The moon is not only a place of challenges, it is also home to a great multitude of resources. The lunar regolith contains a great variety of useful metals, as well as life-sustaining oxygen, and potentially water-ice at the poles. Such materials would not only be useful in the construction and sustainability of a lunar base, they could revolutionize space travel if brought into LEO and used for construction there. Polar ice could be separated into rocket fuel, and pure, untreated regolith could be used for cheap radiation shielding.

The colony will also yield direct benefits to the Earth in both the long-term and short-term. Technology developed for space applications has often found a use on Earth, and the technology developed for this settlement will continue that trend. For example, the plant growing techniques used on the Moon could be applied in urban or water-deprived environments to produce local food while also conserving water. Also, the automated construction developed for the lunar colony could increase manufacturing efficiency back on Earth. Medical technology developed for the colony will need to be very resource-efficient. This technology can then be used in underdeveloped countries to improve quality of life on Earth. The power industry will also profit immensely from the Helium-3 found in the lunar regolith, which could fuel an energy revolution on Earth, should fusion technology significantly advance within the next few decades. The Lunar Solar Plant is another promising power source, which could beam energy to the Earth by microwave transmission. This effort is even likely to improve international relations due to the large amount of cooperation required.

The benefits of a lunar colony can be applied both to humanity on Earth and to interplanetary colonization. Even though challenges will be faced, these challenges will prepare humanity for future expansion to other worlds. For these reasons, a lunar colony should be humanity's first major step toward becoming a truly space-faring species.

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# Appendices

# Appendix A: Power

## 1) Helium-3 as a Power Source

The Earth is running out of conventional forms of energy. Barring any new discoveries, the world's reserves of oil and natural gas will be depleted over the next 50-100 years (Dobransky, 2013, p. 62). Worldwide demand for energy, on the other hand, is expected to increase even more in the next 50-100 years (Kulcinski & Schmitt, 2000, p. 1). Alternative hydrocarbon fuels such as coal will inevitably be exhausted one day. In addition to the depletion of fossil fuels, the carbon emissions of these fuels have also led to rising environmental concerns over their use (Simko & Gray, 2014, p. 150). The geographical and economic constraints associated with renewable energy sources such as solar and wind power makes them unreliable candidates to replace conventional oil.

An energy source that could eliminate these concerns while meet growing energy demands is nuclear energy. Currently, nuclear energy is being generated commercially through the process of nuclear fission, in which heavy atoms of the likes of elements such as uranium or plutonium are split using neutrons. This gives lighter elements and more neutrons which carry on the chain reaction (Simko & Gray, 2014, p. 2). The safety of this process, however, is considered dubious due to the radioactive waste management risks associated with it. The Fukushima and Chernobyl disasters have also severely damaged the public's opinion of nuclear fission energy (Jacobs, 2012). There is also a concern that some countries will use the fission materials like uranium to produce nuclear weapons leading to nuclear proliferation (Kulcinski & Schmitt, 2000, p. 2).

Fission, however, is not the only way to generate nuclear energy. Nuclear fusion is thought to have the potential to generate great amounts of energy without the risks associated with fission.

Unlike fission, nuclear fusion generates energy by the combination of atoms of lighter elements. A commonly researched basic fusion reaction between deuterium and tritium (D-T fusion) is shown below:

deuterium + tritium → neutron + helium

D + T → $^{0}$n (14.1 MeV) + $^{4}_{2}He$ (3.5 MeV)

At the present time, practical reactors have not been able to harness the energy generated through this process. This is because a great deal of input energy is required for this reaction to take place. First the temperature of the fuel must be increased to around 150 million degrees Celsius in order to remove the electrons. Then, powerful magnetic fields are needed to contain the atoms (plasma) that are formed. The input energy therefore becomes greater than the energy that can be obtained from such a reaction. The D-T fusion also produces four times the neutrons released in the fission reaction. About 80% of the energy is released as neutrons. However, it is much harder to harness the energy of these neutrons because they cause significant damage to the surrounding inner walls of the reactor due to their high speed. (Kulcinski & Schmitt, 2000, p. 2). The neutrons themselves are not radioactive but the collide with the walls of reactor, thus turning them radioactive (Simko & Gray, 2014, p. 159). This reaction is therefore even more radioactive than fission and is therefore unviable. Helium-3, on the other hand, can undergo a fusion reaction that does not release any neutrons.

Helium-3 ($^{3}$He) is an isotope of the element Helium ($^{4}_{2}He$), containing one less neutron than the regular Helium atom. It undergoes a nuclear fusion reaction (shown below) with another Helium-3 atom that produces vast amounts of energy.

Helium-3 + helium-3 → 2 protons + helium-4

$^{3}$He + $^{3}$He → $^{1}$H + $^{1}$H + $^{4}$He (12.9 MeV)

There are no radioactive by-products of this reaction, hence completely removing any concerns about waste disposal or public safety. It is also the most efficient fusion reaction in terms of cost and energy. The total reserves of Helium-3 on Earth, however, are only about 300 kilograms (Simko & Gray, 2014, p. 160). The sun generates its energy through a nuclear fusion reaction that forms Helium, some portion of which is Helium-3. This becomes charged as it is taken through space by solar winds and is therefore deflected by the Earth's magnetic fields. The Moon, on the other hand, has no such magnetic field. Over billions of years, solar winds have deposited what are estimated to be 1 million tons of Helium-3 on the Moon (Simko & Gray, 2014, p. 160). This was first confirmed when the samples of moon rock and soil from NASA's very first lunar mission were shown to contain Helium-3 in 1986. Since then, the location and depth of Helium-3 deposits on the Moon have also been established. The deposits can be reached within the first five to ten meters of the lunar surface (Simko & Gray, 2014, p. 160). The method used for the extraction of Helium-3 consists of heating the regolith to a temperature of about 750°C (Wittenberg, 1992). The extraction process, which is discussed in the final report, is therefore rather simple, and the Helium-3 could then be used to generate energy to sustain the moon colony, in addition to terrestrial needs. It is estimated that the entire world will need only about 75 kilograms of Helium-3 per year to meet its energy demands (Simko & Gray, 2014, p. 160), and this could be transported to the Earth using the space elevator or space cargo vehicles.

The problem of harnessing the energy of the fusion reaction still remains. Over the past 50 years, very little has been allocated to the research of nuclear fusion in comparison to other sources of energy. The United States government has very little invested in Helium-3 fusion at this point. The University of Wisconsin-Madison has the only fusion reactor working with Helium-3 in the US and they have an insubstantial budget (Dobransky, 2013, p. 69). They have carried out research concerning the use of an inertial electrostatic confinement which uses electric fields in place of a magnetic field to control the Helium-3 reaction (Kulcinski & Schmitt, 2000, p. 4). Given all of these problems, we are still decades away from a practical reactor with the capability to generate energy from Helium-3 nuclear fusion, and then decades more accomplishing it at a commercial level (Dobransky, 2013, p. 70). In the long term, though, the helium-3 deposits on the moon could sustain the Earth for a thousand years to come. (Simko & Gray, 2014, p. 160). While still not entirely realistic, Helium-3 is definitely a form of energy that could make humanity's presence on earth sustainable and take us into the next century, or even the next millennium.

### 2) Hurdles to Nuclear Fusion, and a Look at Mercury

Can energy generation from nuclear fusion become practical and commercially feasible in the near future? A nuclear fusion reactor with the capability to generate energy has consistently been projected to be five decades away since the Atoms for Peace conference in Brussels in 1958. It is argued that this is in part due to the fact that most of the resources presently allocated to nuclear fusion are dedicated to the Deuterium-Tritium (DT) fuel cycle, which is impractical for two reasons. This cycle shortens the life span of the reactor as 80% of the energy is released as high-speed neutrons that collide with and damage the walls of the reactor. Thus, the reactor would consistently have to be changed after only a few years in operation (Kulcinski & Schmitt, 2000). In addition, it leads to the production of radioactive waste (Williams, 2007). Therefore, this is not a favorable cycle. These problems could be solved using a Helium-3 fuel cycle. The practicality of using helium-3 in nuclear fusion, however, is considered by some to be even more questionable than the D-T fuel cycle.

Presently, most nuclear fusion research is been carried using tokamaks. A tokamak is a device that contains the disassembled atoms or plasma (needed for the nuclear fusion reaction to occur) with a toroidal magnetic field (Hutchinson, 2005). The International Thermonuclear Experimental Reactor, for instance, is currently being built and will be the world's largest tokamak. There is, however a fatal flaw in using a tokamak for Helium-3 fusion. The D-T fuel cycle mentioned above is yet to practically produce energy. In a tokamak, Helium-3 fusion may be even more difficult.

Helium-3 can undergo two fusion reactions. The first, with Deuterium (D-He3 fusion), is shown as follows:

$D + {}^{3}He \rightarrow {}^{4}He + p$ 18.354 MeV

Deuterium + Helium-3 → Helium + proton

(Kulcinski & Schmitt, 2000)

The reaction between deuterium and helium-3 however, is 100 times slower than the reaction between deuterium and tritium. For this reason, attempting to fuse helium-3 and deuterium in an ordinary tokamak would just result in D-T fusion. Hence, this fuel cycle would not be feasible in a tokamak.

The other fusion reaction helium-3 can undergo is with another Helium-3 atom (He3-He3 fusion). The reaction is shown below:

Helium-3 + helium-3 → 2 protons + helium-4

${}^{3}He + {}^{3}He \rightarrow {}^{1}H + {}^{1}H + {}^{4}He$ (12.9 MeV)

(Kulcinski & Schmitt, 2000)

This has an even slower rate of reaction than D-T fusion. To incite D-T fusion, the fuel must be heated to 150 million degrees Celsius (Simko & Gray, 2014). Since He-He fusion occurs even more slowly, the fuel cell would have to be heated to the equivalent of six times the temperature of the sun's interior. This cannot be achieved in any tokamak.

The tokamak, however, is not the only way to carry out nuclear fusion reactions. The University of Wisconsin-Madison operates a fusion reactor that uses inertial electrostatic confinement (IEEC). The reactor is the size of a basketball, hence much smaller in size than a tokamak. It can carry out D-He3 fusion while producing only 2% of the radioactivity that would be produced in a D-T fuel cycle. More importantly, this reactor can also carry out the nonradioactive He3-He3 fusion. Although this research into an IEEC-based reactor is underfunded and concrete developments towards commercial feasibility are still distant, it at least proves that contrary to some suggestions, He3-He3 fusion is theoretically achievable, and perhaps a practical reactor is not as remote a possibility as it seems.

There are also other prospective sources for Helium-3 in outer space. The planet Mercury has been suggested as a potential source for helium-3, although this is yet to be fully investigated. This is due to the fact that when observed from the earth, Mercury is at no time separated from the sun by more than 28 degrees, making it impossible to view from the Hubble Space Telescope. It is also difficult to reach by spacecraft because of its positioning within the sun's gravitational well. The temperature variation of 600 degrees Celsius over the course of one solar day also makes exploration challenging. The Mariner 10 made 3 fly-bys in 1974-75, but was able to obtain images of only half the surface. These images showed the presence of helium-3 in the atmosphere of mercury, as well as hydrogen and oxygen. Mercury is also of interest due to its unique composition.

Mercury was came into being during the same stage of the evolution of the solar system and shares the same processes of creation as the other inner planets (Solomon, 2011). Since the Mariner 10, the Messenger mission has significantly improved human knowledge of mercury. The possibility of using the Helium-3 purportedly present on mercury as nuclear fuel may seem even more far-fetched than lunar Helium-3 mining, but in a future with a permanent foothold on the moon and a well-developed space transportation industry anything could be possible. More comprehensive knowledge of the interrelationship between mercury and its environment could also lead to a deeper understanding of the formation and evolution of earth and planets similar to earth, and in turn, a deeper understanding of the solar system.

### 3) Alternative Nuclear Fusion Systems, and Water on the Moon

The most major hurdle facing the use of helium-3 as an energy source to replace conventional fuels is the practical nuclear fusion of helium-3. To reiterate, at the present helium-3 nuclear fusion cannot be carried out using a tokamak. It has long been argued that alternative technologies to the tokamak should be considered. Continuous inertial confinement is an alternative system for which, it is argued, the physics has been theoretically and experimentally proven, there are no requirements for greater magnetic confinement than tokamaks, there are near-term applications such as ionic propulsion, and the cost of proof-of-concept is relatively low.

One type of inertial confinement is inertial electrostatic confinement, which comprises of a hollow spherical cathode located centrally within a spherical anode containing six ion guns (Hirsch, 1967). These generate positive ions, which are pulled inwards by the negative potential, where they fuse with ions coming from the other direction. Upon fusion they release energy or disperse and then return to the center of the device by climbing the potential hill. The rate of fusion is proportional to the size of the potential well (Kulcinski & Schmitt, 2000).

According to the United States Electric Power Research Institute, the three criteria to determine the practicality of a fusion system are Economics, Public Acceptance, and Regulatory Simplicity (REVKIN, 2012). If one considers the International Thermonuclear Experimental Reactor, it is estimated to cost $17 billion for construction alone. The radioactivity of the D-T fusion reaction – 4 times the radioactivity of nuclear fission – is also going to create problems with public perception. Therefore, tokamak fusion could fail some of the criteria for practical fusion. One type of CIF that could pass is inertial electrostatic confinement, which has been practically demonstrated by researchers at the Fusion Technology Institute at the University of Wisconsin – Madison. This concept, although still not at the point where it can be used for practical fusion, is very small in size – no bigger than a basketball. It is also low in unit cost, especially in comparison to a tokamak. It also has the capability to carry out Helium3-Deuterium and Helium3-Helium3 fusion. Because of its low unit cost, capability to carry out non-radioactive reaction it could meet the criteria of practical fusion systems. IEC also has several near-term applications unrelated to power. Therefore, it could very well hold the key to practical nuclear fusion. It is important therefore, in order to avoid putting all our eggs in one basket, to divert funding to other fusion systems besides tokamak fusion that have great potential.

Whether practical nuclear fusion is achieved using a tokamak or an alternative system, setting up a manned lunar base to mine helium-3 is still a distant possibility. If we are to go to the moon in search for the bottomless resource of energy that can make our presence on earth sustainable, we will have to face challenges hitherto undreamed-of. The idea of colonizing space is not new. In order to create a sustained human presence on the moon, however, we will require a steady supply of water. Relying on water transported to a lunar Helium3 mining base from the earth would not only prove expensive and time-consuming, but could also pose risks to the wellbeing of the long-term inhabitants of the colony in case of delayed or failed delivery. Another method could be to devise a process to obtain water from the moon soil, which might prove expensive and relatively inaccessible.

The Lunar Crater Observation and Sensing Satellite (LCROSS) and Lunar Reconnaissance Orbiter (LRO) found evidence for the presence of water on the moon in 2010. This was done by sending a used rocket stage into the Cabeus Crater and then observing the debris resulting from the impact. The Cabeus Crater was chosen due to its illumination by sunlight and due to the fact that the Lunar Prospector Neutron Spectrometer (LPNS) and the Lunar Exploration Neutron Detector (LEND) showed considerable levels of hydrogen in it. In the debris from the resulting impact, there were indications of the presence of hydroxyl and water vapor, and in a lessor quantity, mineral-bound and metal-bound OH. In addition, hydroxyl radicals that may have been produced through the various processes were also identified (Colaprete et al., 2010). These findings indicated the presence of not only water, but also a complete water cycle. The scientists at NASA contend that since water ice was seen in the ejecting debris, it must have either been carried to the moon, or formed through chemical processes. There are multiple theories for why this water is found the moon. Among these is the accumulation of hydrogen at the lunar poles by solar wind (Crider & Vondrak, 2000). The existence of an active water cycle was inferred from the fact that volatiles such as ammonia, carbon monoxide, carbon dioxide, methane and hydrogen gas made up 20 percent of the debris (Phillips, 2012). According to scientists, these are the result of a reaction between water ice and lunar soil grains, and could also be remains of a comet collision. This showed that the water ice might come from a variety of sources rather than just one.

Once the chemical composition and abundance and locations of this water ice are confirmed, could play a huge role in finally pushing humanity to look for energy on the moon. If we know which regions of the moon have the greatest concentration of water ice, we can build the moon base in a fitting location. One of the greatest barriers to human colonization of the moon could be overcome. Hence, lunar water deposits will play a major role in making lunar Helium3 mining a reality by providing life-support for the inhabitants of a moon base.

In addition to water, the LCROSS and LRO mission found evidence of other substances that could prove useful. As stated above, volatiles such as methane and hydrogen gas were found in substantial amounts, which could be used to provide fuel for the moon base. Besides these, light metals like mercury and sodium were also detected in substantial amounts. These metal deposits could also help sustain the moon base and make it increasingly self-sufficient.

Finally, the detection of water ice possibly resulting from chemical processes occurring on the moon could provide insights into the rest of the solar system. Scientists have posed theories that similar processes may occur on other space bodies, such as asteroids, the moons of Jupiter, Saturn and Mars, and the poles of Mercury. Greater knowledge of the formation of water ice on the moon and the processes behind it could yield a better understanding of Mercury, which could be another source of Helium3 to be utilized in the far-removed but inevitable future.

### 4) Space-based Solar Power

The global environment is changing as a consequence of human activity. The demand for clean, renewable energy is rising not only due to the environmental hazards of burning fossil fuels, but also due to their imminent exhaustion. Space Solar Power (SSP) could theoretically provide an infinite supply of clean energy to humanity. It also has greater power generation, as the solar energy in space is about 10 times greater than on the ground. The power losses due to passing through the atmosphere are also minimized, and solar energy can be harvested for 24 hours, as it is not affected by local time changes. For these reasons, national organizations and corporations from many countries have embarked upon studies into creating a practical Space Solar Powered

Station (SSPS). In the United States, the Department of Energy (DOE), the National Research Council, and the National Aeronautics and Space Administration (NASA) undertook key studies, including the Space Solar Power Exploratory Research and Technology (SERT) program by NASA. Besides the US, the European Space Agency (ESA) and the Japanese Aerospace and Exploration Agency (JAXA) have been prominent. In addition, a number of corporations such as Mitsubishi Electric and Power-Sat are also trying to develop practical SSP systems. Of these programs, JAXA's is the most promising.

JAXA have plans of launching a Solar Powered Station (SPS) by the year 2030. The Tethered-SPS and the Formation Flying Model are two designs being considered by JAXA. Of these the Tethered-SPS is the simpler and more likely to have near-term applications. This design comprised a large solar panel measuring 20 km x 1.9 km and weighing 18000 tons, and a bus system weighing 2000 tons, in addition to 10-km space tether wires (Sasaki et al., 2007). The panel is to be suspended from the bus system positioned 10 km above the panel by space tether wires. The system would be stabilized by the gravity gradient force and remain in geosynchronous orbit (matching the earth's sidereal rotation period) without the aid of any external forces, as the panel experiences the earth's gravitational force and the bus experiences an equal force in the opposite direction. Therefore no attitude control is required. The panel itself consists of 400 independent subpanels, each of which measures 100m x 95m x 0.1m. The subpanels in turn consist of 9500 power modules of size 1m x 1m and weight 5kg, which contain a controller, microwave circuit and power processor. The bus controls the subpanels using a wireless LAN (Local Area Network). The power module incorporate thin film solar cells on both the top and bottom surface, while the microwave transmitter antennas are on the bottom side, enabling it to generate a maximum power of 490 W, and transmit a maximum of 420 W via microwaves. Thin film solar cells comprise a thin film of photovoltaic material (which produces a current when struck by light) such as silicon on a substance such a glass or metal. The large array of solar cells will convert solar energy to direct current (DC) with an efficiency of 35%, which will then be converted to microwaves with an efficiency of 85% in the power module. The antennas on the bottom surface would then transmit the microwaves as a very precise beam to receiving rectenna - a device that incorporated an antenna, input filters, a rectifying diode, and an output filter – the ground that convert the microwaves back to DC power, which is fed into the grid.

This system can be demonstrated on the ground by using a super-pressure balloon of $1000m^3$ to lift a scaled-down system of 800kg. The balloon is attached to the ground to simulate geosynchronous orbit, and 17.5 W of power is transmitted using microwaves, of which 7W is received by the rectenna. There is also an experiment planned to demonstrate the system in orbit. In theory all of this is achievable, however, there are some major practical hurdles. Firstly, the efficiency values for the conversion of solar to DC and DC to microwaves are beyond the capabilities of current technologies. It is expected that in the next 20 to 30 years, technological advances in photovoltaic cells and microwave circuit will make is possible. Space tethers in the range of 20km have been successfully deployed in space the past, but solar panels of such a scale have never been deployed before. The 4.6m x 32m solar panel array deployed on the International Space Station does offer some hope. Another hurdle would be the transportation and construction of the Tethered-SPS. The subpanels would be transported from the ground to the low-earth orbit (LEO) at around 500km on a reusable launch vehicle (RLV) in unit cargo packages of 95m x 10m x 10m. It would then be moved to an Orbit Transfer Vehicle (OTV) to be transferred to geo-synchronous orbit (GEO). A typical 200 MT OTV with electronic propulsion of 80N thrust would accomplish this in four months.  The subpanels would then be unloaded from the cargo and would automatically deploy into geo-synchronous orbit. After a functioning test, robotic docking assistants would assimilate the subpanels into the SPS. With such space vehicles, this process could take a great number of round trips to GEO and back to the ground and would hence prove very time-consuming and expensive. Therefore, efficient space transportation is imperative to the success of the SPS program. In addition, robot technology that can be remotely controlled from the ground must be developed to complete the assembly of the SPS in GEO.

One problem that is common to all SPS designs using microwaves is the control of the microwave beam. In order to accurately aim for the receiver rectenna on the ground, the deviation of the beam has to be less than 0.2 degrees (Yoshino, Shinohara, & Mitani, 2014). This is very difficult to achieve, as all the transmitting antennas on the panel are independent of each other and must be controlled and moved separately in order to ensure the beam aims correctly. One way to rectify this is by way of maximizing transmission efficiency. For this purpose, solid-state amplifiers can be used to form a beam of sufficient power. As a result of design improvements in recent years, their efficiency has rose to as much as 80%. Another method is retrodirective beam control, which is accomplished by retransmitting the phase conjugate of a pilot signal from the ground. A phase conjugate transforms the signal so that the amplitude and frequency remain unchanged but the direction of propagation becomes the opposite. This signal will point to the source, which is the ground, thus decreasing deflection (Jaffe & McSpadden, 2013). Increasing the size and number, and maximizing the efficiency of the rectenna at the receiving site can also help cut losses and increase the amount of power that is received. Another approach could also be to install a second satellite closer to Earth and use it to receive and then retransmit the microwave beam to achieve greater accuracy by reducing distance.

Another issue related to the Tethered-SPS is the variation in power generation. As a result of the gravity gradient, which keeps the SPS in geosynchronous orbit, the bottom surface of the panel would always stay parallel to the surface of the Earth. Hence, as the angle of incidence of sunlight varies with change in time from day to night, the angle of the sunlight striking the panel would also vary. Hence, the power that can be generated by the Tethered-SPS is 64% of the maximum power provided by the sunlight. When the area covered by antennas and the efficiency of the solar cells is taken into account, this effectively becomes 60%. Although this percentage is still 4-6 times greater than the solar power harvested by ground solar systems, it still poses an efficiency problem. One possible solution could be to change the inclination of the panel by altering the length of the space tether wires in order to improve the angle of incidence of the sunlight. This is a method that is sometimes used to control the surface shape of the primary mirror of large telescopes. Using the Formation-Flying SPS could also solve this issue as it is free moving and can always keep the incidence angle of sunlight at 90 degrees. The Tethered-SPS, however, is not without its own advantages.

As previously stated, the Tethered-SPS system requires no attitude control. Since there are no moving parts, it is a very stable structure. The standardized design and size of the subpanels also makes the gradual construction and maintenance fairly easy. In addition, the lack of any connection between the modules of the subpanels allows for easier deployment. The capability to experimentally demonstrate the system on the ground as well as in orbit can also mitigate some of the economic risks associated with such a large-scale project. The Formation-Flying SPS design is far more advanced, ambitious, and efficient in terms of power generation and will most certainly become more appealing as the concept becomes concrete, but in the nearer future the Tethered-SPS design will prove to be a vital stepping-stone in our voyage through space.

### 5) Lunar Solar Power

Ground-based solar power systems can only collect the sun's energy during the daytime and are intermittent due to variation in weather. Even the most sophisticated solar cells have an efficiency of only 30%. As a result, solar farms covering vast areas are required to fulfill the world's energy needs. In the case of the United States, 20% of the total land area would have to be covered in solar farms in order to provide for the country's energy needs. This makes solar power an unlikely candidate to replace fossil fuels. Since the solar energy is 10 times greater in space, the Solar Power Satellite (SPS) systems currently under research at the Japanese Aerospace and Exploration Agency could be a great possibility. However, with current SPS designs and space travel and docking robotics technologies, these systems would prove very costly. In order to meet the energy needs of the planet, about 6000 SPS systems would be required, which would involve carrying payload weighing an aggregate of more than 300 million tons geosynchronous orbit. This would bring up the cost of power immensely. Therefore with current technologies an SPS is impractical. With more long-term research into SPS design and by lowering the cost of space travel, JAXA's design may be brought to fruition, but for the present we must look at another way to harness solar energy in space.

Fortunately, there is a natural satellite with a steady orbit that could perform the functions of the SPS by generating energy in space. The moon receives constant sunlight all year round, barring a complete lunar eclipse, which only takes place once a year and lasts around 3 hours. All in all, 13000 TW of solar power are transmitted to the moon every year. This would easily fulfill the 20TW global demand for power, even after accounting for energy losses (D. Criswell, 2002). A Lunar Space Power (LSP) system could be used to harness this power. The moon is a very suitable place for a solar power system. There is no damage to the materials due to chemicals or oxygen in the atmosphere, wind, rain or dust, and there are no major disturbances as moonquakes and meteorite impacts cause very little motion. There are vast areas available to set up great numbers of solar arrays. The concept of the LSP system would essentially be very similar to the design of the JAXA SPS. It would require multiple moon bases to collect the solar energy incident on the lunar surface, which would be converted to DC power, which in turn would be converted to radiofrequency (microwaves). The microwaves would be concentrated into accurate beams and transmitted either directly to earth, or to satellites in the earth's geosynchronous orbit, which would receive and then retransmit the microwaves to rectifying antenna, or rectenna on the earth's surface.

For this specific design, it is estimated that 10 to 20 bases will be required to meet the world energy demand. Each base will consist of a pair of bases, each implementing part of the operation. Base 1 would be built on the eastern or bright side of the moon and Base 2 on the western or dark side as seen in the diagram with respect to earth. The collection of solar energy would take place on Base 1 in the very basic unit of the power station: power plots. The power base, Base 1, would contain power plots in the range of tens of thousands on the equatorial lunar area. Each power plot would work in four stages. Solar arrays covered in thin-film solar cells would collect sunlight and harness its solar energy. This energy would be converted to electrical energy by solar convertors.

The collected energy would then be carried away to the corresponding Base 2 in electrical transmission lines. The Apollo Lunar Surface Experiment Package (ALSEP) already demonstrated the use of power lines on the moon in 1969 (D. R. Criswell, 2000). Burying the wires under the lunar surface at a shallow depth could keep them safe from damage due to space weather or solar radiation. The wires would have to be very thickly insulated to avoid overheating due to Ohmic heating. At Base 2 on the other side of the moon, convertors would convert the DC power to microwaves, which would then be transmitted to microwave generators at the power base in transmission lines. At the microwave generators, the microwaves will be formed into a single microwave beam of appropriate amplitude, phase and frequency. These would be directed to a mirror or screen, which would deflect the beam towards rectennas on the earth directly or via earth orbiting relay satellites. A concept could be borrowed from the formation-flying SPS design to increase the incidence of sunlight rays onto the arrays. Small solar sails could be deployed in large numbers to orbit the moon and deflect sunlight to the solar arrays. Solar sails (shown in Figure 27) are a type of spacecraft that require no propulsion, making use of the solar radiation pressure force to drive ultra-thin mirrors through space. A solar sail could deflect sunlight to multiple power plots for a small duration of time as it passes over, and then be replaced by another solar sail while it moves on to another section. These would be especially useful in collecting energy during the lunar night and eclipses.

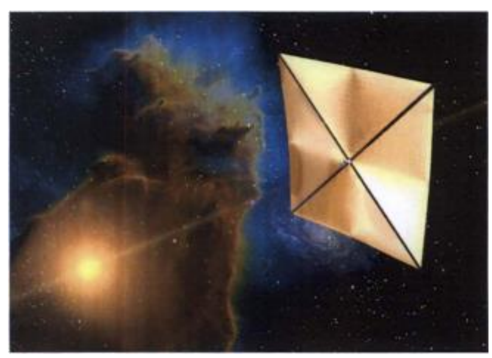

*Figure 27: Solar sail (artist's representation) (Young, 2006)*

A relay satellite may be used to redirect the microwave beam so that it could converge at the rectenna and reduce stray microwaves thus reducing power losses. Although relay satellites are not required to make LSP a reality, they could significantly lower costs for the system by increasing the margin for accuracy at the LSP system. There are two types of satellites that could be used, reflector and retransmitter satellites. A reflector satellite would have a partly similar to the formation-flying SPS, in that it would use mirrors to deflect the beam to rectenna. For a 2.54 GHz system with a 0.5km diameter rectenna site, a reflector satellite would have to be 1-2km in diameter at 6000km in altitude (medium earth orbit). However, switching to 5.48 GHz and increasing the size of the receiving site could decrease the required diameter. The International Space Station has a 100m long backbone, which may be used as a reflector satellite. However, switching between different rectenna without changing position and keeping accuracy will present challenges to using the reflector satellites in conjunction with the LSP system.

A retransmitter satellite would be more advanced but also more effective. It could make use of the already existing technology of flow synthetic aperture radars (SAR) under use at NASA and the European Space Agency. The Shuttle SAR, which consists on a planar antenna with 1044 transmitters with the capability to beam the 2.45 GHz microwave frequency, can practically validate this concept.

Using this type of satellite, the single beam can be retransmitted as several lower energy beams to different rectenna on the earth, thus requiring a smaller number of relay satellites. It can also be adjusted to meet the load demands at each rectenna. Part of the power received could potentially be stored in the satellite to meet its own energy demands for attitude control. A retransmitter satellite would therefore carry a lot of advantages over the simple reflector in transmitting microwave beams to the rectenna. As for the rectenna design, it would be similar to the SPS receiving system, with a lightweight structure making use of printed circuitry (D. R. Criswell, 2000). In the final step the microwave beams would be transmitted to the rectenna at the receiving site.

The construction and maintenance of such an LSP system would require the use of manned and unmanned vehicles with the capability to reach the moon. Various countries have demonstrated this in the past. In addition, building and maintaining such a large-scale project will require advanced robotic assistance. There would also be the risk of degradation of surfaces and materials due to the massive amounts of solar radiation, huge temperature fluctuations (100 degrees Celsius during the day to -173 degrees Celsius during the night) and direct meteorite impacts. These risks would also be detrimental to any inhabitants of the LSP system. But the benefits outweigh the risks. One of the most significant outcomes would be the colonizing of the moon. The power would enable us to use lunar materials such as the regolith to produce oxygen and metals (Schwandt, Hamilton, Fray, & Crawford, 2012). LSP would pave the way for a self-sufficient lunar colony. The colony could be used for a variety of purposes, such as tracking near-earth objects. The power generated could be beamed to power other space bases such as the International Space Station. In the long run it could facilitate the mining of Helium-3 and rare-earth materials from the moon. Theoretically it could even beam microwaves to space vehicles, which could be converted to electrical power onboard, thus enabling further space exploration. Lunar Space Power could be technologically achievable very soon and could also be made very cost-effective if local lunar materials were used in construction and maintenance. It will certainly be an attractive solution to the world's energy problems.

## 6) Powering the Moon Base: Final Lunar Solar Plant design, And Nuclear Reactor comparison

The type of power supply chosen for a moon base depends largely on the long-term and short-term power demands of the mission. The number of crewmembers, the various facilities at the base such as research and materials processing, and the general objectives would influence these demands. The power system to be used during the initial stage of the development of the moon base will vary based on the power requirements. If the power in the range of 100kW or more is required immediately to begin the development process, a nuclear fission reactor might prove more favorable than solar power.

NASA has considered a modified SP-100 system in the past (Hickman, Curtis, & Landis, 1990). This is a lithium cooled, fast spectrum system, fueled by uranium nitride (Smith, 1988). It would have enough fuel to last 7 years, with a power generation in the range of 100 to 400 KWe. With a weight of 4500kg, it could be installed on the lunar base in the early flights. It would provide the power required for mining and lunar materials processing, thus allowing for in-situ materials utilization from the moon. However, the SP-100 concept may prove very expensive, as the program's funding was withdrawn after an investment of $415.2 million (McGinnis, 2004). Another nuclear powered alternative design that may be considered is the HOMER-25, which uses heat pipes to produce 25KWe of power from Stirling engines (Poston, 2001). These could be significantly cheaper than the SP-100, but it is possible that as the design progresses the cost projection will increase as it did with SP-100. This would only weigh around 1385 kilograms. Therefore, 4 HOMER-25 reactors could be taken to the base as a single payload weighing only 5540 kilograms. This would also allow us to use them at multiple sites on the moon. These reactors have a lifetime of 5 years in power.

The final design under consideration is the Space Molten Salt Reactor. This reactor is unique in that the fuel is in molten form, unlike the solid fuel of most fission reactors today, including the SP-100 and HOMER-25 designs. While the specific concept in question uses a LiF, $BeF_2$ and $U235F_4$ based fuel; this design is capable of using a range of different fuels. With respect to the resources available on the lunar surface as well as terrestrially, the most well suited fuel for the lunar colony is the Liquid Fluoride Thorium fuel. Such a fuel would bring with it the benefits of a molten fuel, in addition to being powered by Thorium rather than Uranium. Terrestrially, Thorium has 3 times the reserves of Uranium (“World Nuclear Association”). Cost will be an important factor during the early phases while the colony tries to establish economic viability, and thorium can lower initial fuel costs. An even bigger advantage can be gained during the in-situ resource utilization phase, if the deposits of thorium found by the Lunar Prospector spread throughout the moon’s Mare Ibrium, Mare Oceanus Procellarum, and the South Pole-Atkin Basin (Lakdawalla, 2011) can be tapped. The Liquid Fluoride Thorium fuel is also less likely to cause nuclear proliferation as compared to the Uranium based reactors. The LFT reactor design is also safe from any possibility of a meltdown (Juhazs, 2009). Therefore, it will be the safest for the inhabitants out of the three reactors. Moreover, the SMSR concept has a very basic design in contrast with the more complex designs of SP-100 and HOMER-25, which could yield a lightweight near-term application of the reactor. A terrestrial model of a reactor with a liquid fluoride thorium fuel is estimated to cost $200 million, and the SMSR would be a much smaller scale model so low-cost could be expected. An itemized comparison can be seen in the Figure 28.

The nuclear reactor could also serve as backup to the solar power in cases of emergency, and during the lunar night. However, the reactor would need to be installed as far from the base as possible while minimizing cable transmission losses (about a kilometer), and buried underground in order to mitigate radiation dangers and provide thermal insulation.

| Reactor Design | SP-100 | HOMER-25 | Space Molten Salt Reactor |
|---|---|---|---|
| **Fuel type** | Solid Uranium fuel | Solid Uranium fuel | Liquid Fluoride Thorium fuel (thorium 3-4 times more abundant than Uranium) |
| **Mass** | 4500kg, it can be stowed and taken to the moon as a single payload. | At 1385kg each, multiple reactors could be carried as a single payload | Conceptual stages. Simplistic design could lead to lightweight model |
| **Power generation capacity** | Capacity of 100 KWe to 400KWe; one reactor will be enough to meet the power demands of the base | Capacity of 25 KWe; 4 reactors will be required to meet power demand of 100KWe | Capacity of 100KWe to 15MWe Could be expanded to meet growing energy demands |
| **Projected cost** | 420 Million invested until withdrawal of funding, ground testing yet to begin | Low-cost may be possible, but costs may rise as time goes on | 100 MWe Terrestrial molten salt powered reactor design is projected to cost $200 Million, so 100KWe model could cost significantly less |
| **Life span** | 7 years | 5 years | Not Predicted |

*Figure 28: Comparison of reactor types*

A more time-consuming but certainly safer power source is a lunar solar power station. Photovoltaic array designs similar to the ones used on the International Space Station can be used. One such array measures 33.528 m by 11.5824 m, covers an area of approximately 3883 sq. meters and consists of 32,800 solar cells. Gallium-Arsenide cells would provide the best conversion efficiency and highest temperature resistance out of the technology available today (Trochynska, 2009). The specific model to be used is InGaP/GaAs tandem solar cells, with efficiencies of 37.9% (Green, 2014, p. 207).

In the future, quantum dots could be considered which can increase the efficiency to up to 66% (Nozik, pg116). They can increase efficiency by using the same approach used in semiconductor cells – by using a number of p-n junctions to reduce heat loss, and therefore power loss, except they can have an unlimited number of p-n junctions. A simple triangular configuration would be used for the arrays in order to maximize power generation during the daytime. Each array provides a nominal power output of about 11kW. A 100 KWe power plant would consist of 10 such arrays, mounted on pole mounts. These would consist of poles driven into the ground, holding the array in place. Such a mounting system is fixed and cannot change the orientation of the array in accordance with the angle of incidence of sunlight, but it has advantages in that no steel or concrete base is required to embed the mounting system. This will reduce the mass of the earth and lunar materials required to construct the system, thus decreasing transportation and processing cost. The angle of the sunlight will affect the power generation greatly, however, and this will require mirrors or solar sails to increase the incidence of sunlight onto the arrays.

Different ways could be used to increase the incidence of sunlight on the fixed solar arrays. Mirrors similar to the formation-flying SPS model could be placed above the power station. The orientation of these could be changed accordingly to decrease the angle of incidence of sunlight onto the arrays. However, there would be a need for a constant power source for attitude and orientation control. Another method would be to put large number of low-cost solar sails in orbit around the moon. These would also require no propulsion as they are propelled by solar radiation. These sails would push thin mirrors through orbit, deflecting sunlight onto the arrays as they pass over. These would also be required in huge numbers for there to be a constant presence over the arrays. A disadvantage would be the inability to change the orientation of the sails, but using multidimensional mirrors could mitigate this.

The location of the solar power station will be another key issue. The "eternal peak of light" at the rim of the Shackleton Crater would be ideal, as it experiences almost continuous sunlight all year round. This would be especially favorable for the initial stage as the Shackleton crater on the South Pole is the favored location for the base, and this would greatly reduce power transmission distance. As the base expands with increasing number of facilities, however, the power demand will increase correspondingly and the power station will have to expand as well. In order to provide both the base and the power station with ample space to expand, the North Pole may be a more favorable location for the power station. It also has areas that experience near constant sunlight. Power could be transmitted between the poles through electric transmission lines, the use of which has been demonstrated by ALSEP on the moon. In order to protect them from the various damaging effects of the lunar environment, these wires could be buried 50cm underground and insulated heavily to contend with the Ohmic heating effect.

Some of the environmental phenomena that could potentially damage the solar power station are solar radiation, fluctuations in weather, solar flares, micrometeorite impact and dust. The ISS in lower earth orbit undergoes 4000 thermal cycles per year, whereas the lunar power station would only undergo 600 cycles over a period of 30 years, so degradation due to changes in temperature will be a lot slower in comparison. The arrays of the ISS have an operational lifetime of 15 years, so with respect to thermal changes the LPS arrays could have a much longer lifetime, especially as the polar regions of the moon have significantly smaller fluctuations of temperature.

In order to have a functional solar power plant before the arrival of the first crew, preparative work will begin a year in advance. A crew of 2 will be required for initial assembly and set up of robotic assistants. The initial plant can have a capacity of 100 KWe by the end of the preparatory year. Following the arrival of the first crew, this could be expanded according to the growing need for energy. About 3KWe will be required for each crewmember (McGinnis pg.1). The power required to support the first crew consisting of 7 crewmembers would therefore be about 21 KWe. In addition, power required during excavation and preparation of the site, and construction of the base will also need to be calculated accurately in order to obtain an estimate of requirements.

Studies on sites for the construction of hydrogen-oxygen fuels cells to store excess solar power generated during the day for the lunar night must be begun during the first phase. Backup power systems will also be required to ensure the base has power during an eclipse or in case of emergency failure of primary system. Once the solar plant is complete, the nuclear reactors will be used to provide backup for the duration of their lifetime. However, this is only 5 to 7 years for the two systems discussed, and replacement would be expensive, as it would require the transportation of large payloads. Therefore, rechargeable Lithium Ion cells will be used. These charge when lithium ions flow between a positive and negative electrode (Horiba, 2014). A single unit provides power in the range of hundreds of watts, but they are lightweight and portable, so many units can be used in combination. These would provide power for life support in emergencies.

The short-term goals would be to expand the solar power plant to 200 KWe by the end of the first year of operation, and to expand by at least 100 KWe in each subsequent year. By year 10, research could be begun into beaming power to earth using experimental microwave generators and transmitters. The long-term plan would be to have a capacity of 13 TW by 2050 to meet the Earth's demand for energy.

## 7) ISRU

There are about 20 methods of Oxygen extraction that have been suggested by researchers thus far (Eckart, 1996, p. 88). Among these is fluorination, in which the oxygen present in the form of metal and silicon oxides is separated from the regolith by reaction with earth-based fluorine at 500°C, and captured for use (Landis, "Materials Refining on the Moon", p. 507). This reaction converts the oxides present in the regolith to fluorides, from which metals and silicon must be extracted. This is done in a separate reactor system by adding earth-based Potassium to the remaining regolith, which separates the fluorine yielding Iron, Aluminum, Calcium, Magnesium, Silicon, Titanium and other trace materials. While it is simple, fluorination requires a higher amount of power and a relatively smaller percentage yield than various other methods.

Another method under consideration is the reduction reaction of ilmenite. In this approach, Ilmenite – which has the chemical formula $TiO_2$ (Titanium Oxide) – undergoes a reduction reaction with Hydrogen to yield water. This water is then pumped to Regenerative Fuel Cell and electrolyzed to produce Oxygen and Hydrogen as needed. Although this method uses even slightly more power than Fluorination, it has one of the highest yields of Oxygen. It is also useful in that it produces water, which is another essential consumable that must be produced or extracted in-situ if the colony is to be self-sustainable.

Finally, the molten electrolysis of oxides especially silicates is potentially the most attractive method for oxygen extraction. This method uses electrolysis to reduce metal oxides and silicates to yield oxygen, metals, and Silicon dioxide. It can be summarized in three reactions. These reactions occur at the cathode:

$Fe^{+2} + 2e^{-} \longleftrightarrow Fe^{0}$

$Si(IV) + 4\ e^{-} \longleftrightarrow Si^{0}$

At the anode, there is only one reaction:

$4(SiO^{-}) \longleftrightarrow 2(SiO_2) + O_2 + 4e^{-}$

The final product of these reactions is Oxygen, whichever metal was used at the cathode, and a Silicon-Iron alloy. Therefore, this process can both extract Oxygen and produce metals as byproducts in simultaneously. It is also favorable because it uses lesser power than both ilmenite reduction and fluorination, and has a high yield relative to per consumption. In addition, it does not require the regolith to be beneficiated. Therefore, this is the most efficient method for producing Oxygen. A schematic below shows the basic working of this method.

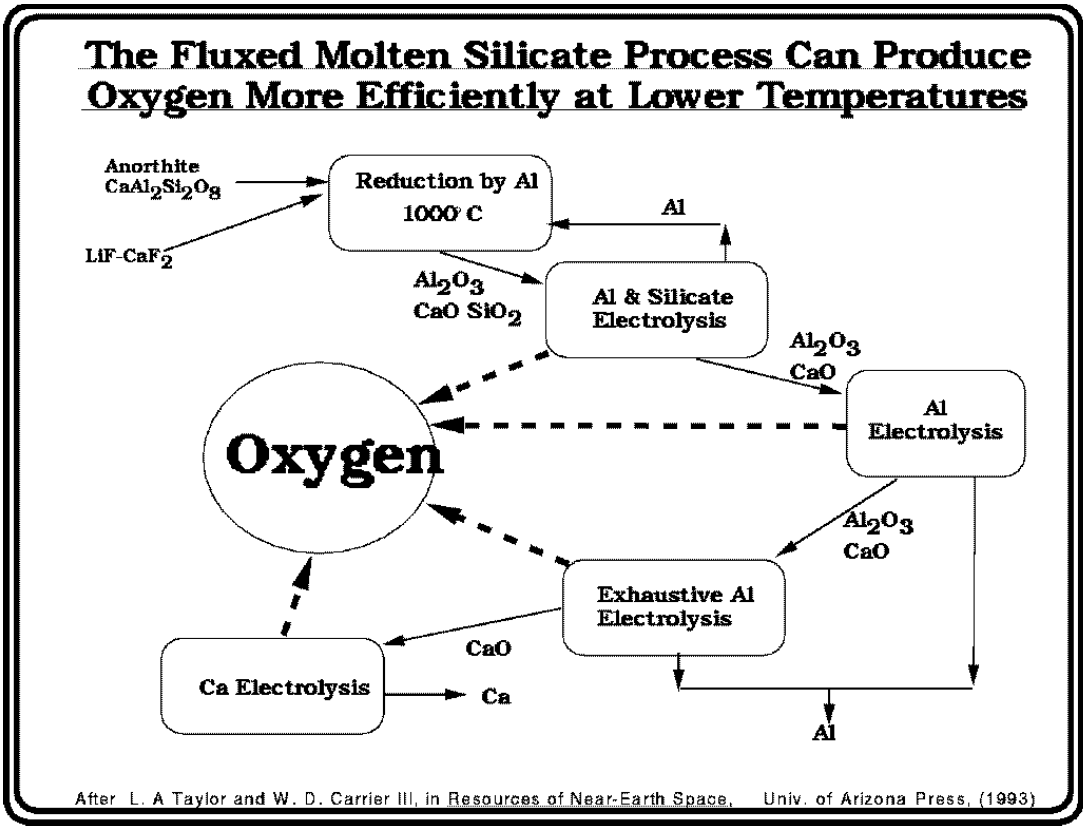


*Figure 29: Fluxed molten silicate production of oxygen*

A more detailed structure is given below, showing an electrolysis chamber with 4 anodes (labeled electrodes) and cathodes, containing regolith in molten form. The Oxygen is collected at the top, and the other byproducts through taps on the right hand side.

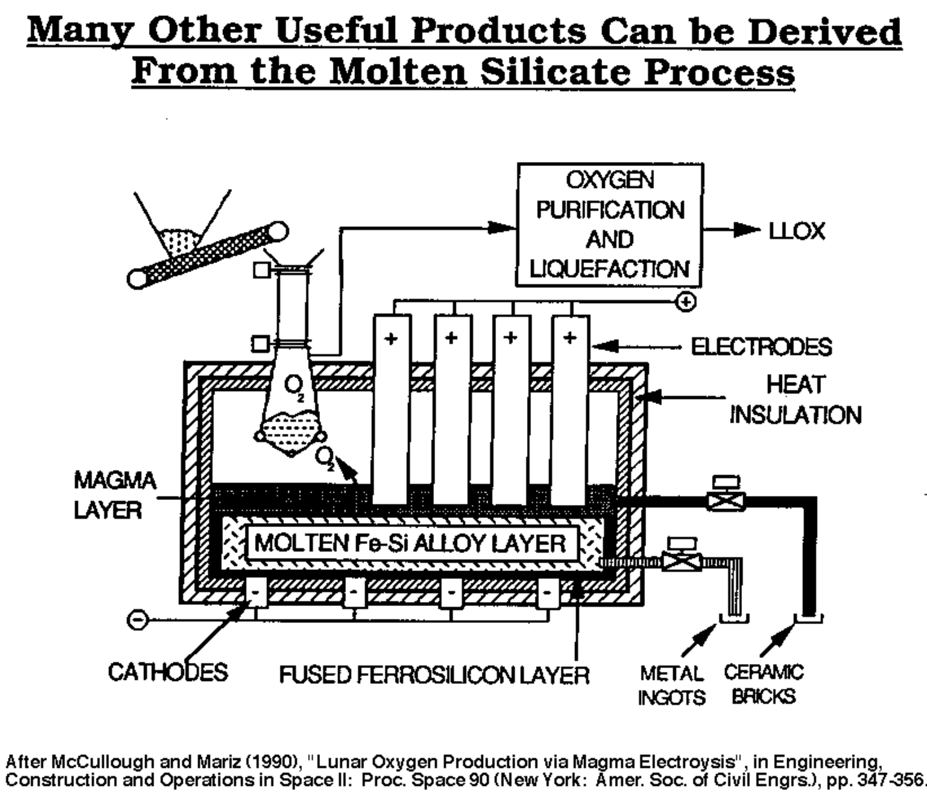


*Figure 30: Products derived from molten silicate process*

Some of the operating conditions of this method and the advantages it holds over other possible methods are summarized in Figure 31 (Haskin 1990, p. 206).

TABLE 9. *Comparison of Proposed Processes for Producing Oxygen From Lunar Soil*

| | Electrolysis | Typical range for alternative processes* |
|---|---|---|
| Feedstock | Common soil | Common soil to beneficiated soil to ilmenite |
| Mass of mined material (per 1000 tonnes O2) | 4 670 tonnes | 4 600-120 000 tonnes |
| Reagents required | None | None to C, H, F |
| Temperature | 1250-1400°C | 700-3000°C |
| Plant energy (per tonne O2) | 13 MWhr (47 GJ) | 20-40 MWhr (72-144 GJ) |
| Plant mass (per 1000 tonnes O2 per year) | 3-10 tonnes | 5-80 tonnes |
| Product | Oxygen, Fe-Si alloy, slag | Oxygen with pure oxides or metals to oxygen plus slag |
| Primary advantage | Simplicity | E.g., good Earth analogs for process, many usable products, no consumables used, low-T operation |
| Primary disadvantage | Corrosive silicate, high-T operation, difficulty restarting after cooldown | E.g., complexity, high-T operation, low oxygen/reagent ratio, low product/ore ratio, high energy or mass required |

*Values calculated from Eagle Engineering 1988 and references therein.

*Figure 31: Processes for Producing Oxygen from Lunar Soil*

This table shows the advantages molten electrolysis possesses over other processes. It does not need soil to be beneficiated unlike in some methods, which and so will not be impacted in any inefficiency in the beneficiation process. The mass of regolith required to produce 1000 tonnes of Oxygen is in the lower range; electrolysis requires 4670 tonnes while other methods require a range of 4600 to as much as 120000 tonnes. There are no reagents needed for the reaction to take place, unlike the fluorination process that requires F2 to extract Oxygen and then Potassium to separate the metals, both of which have to be resupplied from the Earth, and the ilmenite reduction process that requires Hydrogen, a precious resource on the moon. The temperature required for the reaction, however, is rather high at 1250 -1400 °C. In contrast, the operating temperature for

Ilmenite reduction is 900-1050 (Eckart, 1996, p. 89), whereas fluorination takes place at 500°C as stated earlier. Luckily, the high temperature requirement does not translate to high power consumption in the case of molten electrolysis, as there is a significant decrease of 7MWhr in the power requirement compared to the other processes. Finally, the mass of the set-up is also the lowest of all the methods at 3 to 10 tonnes, which is testament to the minimalism of the process and its apparatus. The issues arising from corrosiveness, struggles to revive the system after cooling, and the high temperature are under investigation. Thus far, experimentation has been carried out with materials such as platinum for the electrodes of the container and MgAl2O4 for the container, with some success. This will be researched in depth at the lunar outpost in preparation for the pilot ISRU program in Phase 2. Taking everything into account, molten electrolysis appears to be the best method at the current time, but further investigation is required into all other methods for there to be a definitive answer.

# Appendix B: Space Elevator

The concept of a geostationary satellite can be envisioned as though the satellite were perched atop a tower 36,000 km high, the top of which would be moving with such horizontal velocity that any object released would enter a perfectly circular orbit around the Earth. But what if such a tower could actually be constructed? In the sense of a tower, such a thing would be impossible. There is currently no known or theoretical materials that could support its own weight to a height of 36,000 km and remain rigid. If we approach the problem from a different angle, however the concept enters the realm of feasibility. If we were to instead hang a cable from a place just above geostationary orbit (GEO), connected to an anchor station on the equator, and then further connected to a large counterweight in a higher orbit, such a system would be well within the realm of possibility. If such a system could indeed be built it could offer an enormous range of benefits to our future exploration and use of space.

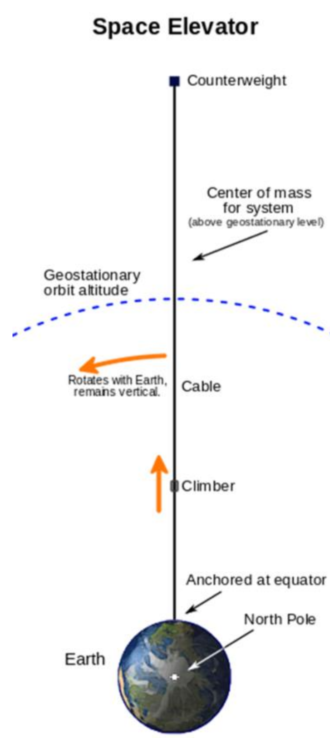


*Figure 32: Diagram of Earth-based space elevator ("Space Elevator", 2014)*

This design for a space elevator has four main sections: the cable, the counterweight, the anchor, and the climber(s). The basic principle behind this design is that at 35,786 km above the surface of the Earth, the period of a circular orbit is exactly as long as an Earth day. A satellite in such a circular orbit is traveling at a great enough velocity that its acceleration due to gravity is exactly cancelled out by its angular acceleration by this relation: $a = -{GM}/{r^2} + \omega^2 r$. Where ω is the angular velocity of the Earth's rotation and is equal to $7.27*10^{-5}$. (Pearson, 1975) As a consequence, an object with the same angular velocity in a lower orbit would have a net acceleration towards the Earth, while an object in a higher orbit with the same angular acceleration would have a net acceleration away from the Earth. Now if we think about a cable reaching from a satellite in GEO to the surface, we can see that the entire cable will be pulled towards the Earth, as it would have the same angular acceleration as the satellite, but reside in a lower orbit. This necessitates another section of cable reaching up above GEO, which would instead have a net acceleration away from the Earth. This counterweight would serve to counteract the net force of gravity on the lower section of cable, help place the center of mass of the entire system above GEO, and would provide additional tension, so as to keep it taught along its entire length. The counterweight would either need to be extremely massive or be placed in quite a high altitude as the force due to angular acceleration increases linearly with distance, while the force due to gravity decreases by the square of the distance. One proposal puts the counterweight at a height of 144,000 km compared to the 36,000 km altitude of GEO (Edwards & Westling, 2003). For comparison the radius of the Earth is only 6,371 km, so such a cable if laid flat could circle the Earth a few times over. Once this cable was established, it could be scaled by mechanical climbers which could haul cargo into orbit using only however much energy was needed for them to scale the cable. The energy for the change in velocity as the climbers ascend would come from the rotation of the Earth. As the climbers ascend, they would start moving slower that the cable they were ascending, causing a small amount of drag westward, slightly slowing the rotation of the Earth. The Earth possesses so much angular momentum that this slowing is negligible.

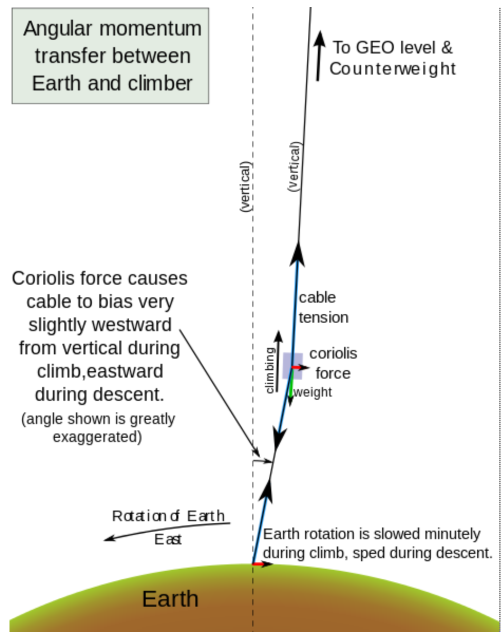


*Figure 33: Angular momentum transfer of space elevator-Earth system ("Space Elevator", 2014)*

While a space elevator of this sort is quite possible in theory, there are a number of challenges in each of the four main parts of its design that must be overcome before construction can even enter its preliminary stages. Firstly and perhaps most importantly is the design of the cable itself. The material used to create the cable must be both incredibly light and strong. Carbon nanotubes could potentially be used for this purpose, but as of now can only be manufactured in lengths of a few centimeters, and cannot be created in bulk. Most design proposals have favored a ribbon design that would taper in thickness from the center of mass to each end, so as to maintain a roughly equivalent strain across its entire length. A ribbon design would be more resilient to micrometeorite impacts, as well as being easier for the climbers to scale. The design of the cable is perhaps currently the largest obstacle in the creation of a functional space elevator design.

Another aspect of the design is that of the surface anchor, of which there have been two major designs proposed. The first is that of a floating, sea based platform, which could move to avoid weather and space debris that could threaten the integrity of the cable, as well as avoiding political disputes over the use of land on the equator. The second major design would be a land based anchor which would provide a more stable platform as well as the potential to be built at high altitudes, either atop mountains or tall towers, reducing the required length of cable.

The third major piece of the puzzle is that of the mechanical climbers which would ferry cargo between the surface and orbit. Most design proposals include a pair of rollers clamped onto the cable that would pull the climber up its length. One unavoidable aspect of the climber design is that even if it went at a relatively quick pace, it would still take days to reach GEO, during which time it would pass through the Van Allen radiation belts, and would remain within them long enough for passengers to receive radiation sickness. As such, climbers would either have to be designed with extensive radiation shielding, which would add significant weight, or solely be used for cargo and not passengers (Edwards & Westling, 2003). Another challenge in the design of the climbers is in how they would be powered. The currently agreed upon solution is to beam power to the climber from the anchor station, either by laser or microwave beam. Unfortunately this limits climber ascent to periods of uninterrupted clear skies for continuous operation.

The final major section of the space elevator design, the counterweight is perhaps the most flexible in its design. A number of different things could be used as part of a counterweight, such as a captured asteroid, gathered space junk, or even the equipment used in the initial construction of the cable. No matter what it starts out as however, the counterweight could be converted into a docking and launch station. A counterweight at an altitude of 144,000 km would have a net acceleration of about .8 $m/s^2$ or nearly .1 G, and would be moving fast enough that any object detached from it could potentially be flung past the orbit of Jupiter, and with an additional gravity assist, could be sent on an interstellar trajectory, all without the use of any propellant. With these two factors, the counterweight could even be turned into a construction and launch platform for interplanetary missions.

Aside from the design of its component pieces, there are a number of other challenges that must be overcome in the construction of a space elevator. Firstly and most importantly is the matter of construction. Assuming we could create a cable with the necessary strength to density ratio, how would we actually get it into orbit and properly attach it at both ends? One proposal suggests launching a craft with a thinner "seed" cable which would connect to a ground station which would then send specialized climbers that would splice new cable material onto the existing cable as they ascend, before becoming part of the mass of the counterweight. Over many successive climbers the cable would become more and more robust before reaching its optimal thickness and begin ferrying cargo into orbit.

Besides construction, there are a number of risks involved that must be accounted for. First of these is the ever present threat of space debris. Given an infinite amount of time, every satellite or piece of debris not in a synchronous orbit will impact the cable at some point in the future, the majority of them large enough to cleave such a cable in two. Active satellites could be maneuvered away with their on board thrusters, but the many pieces of uncontrollable space debris would still pose a serious problem. Unless the majority of this debris were deorbited or otherwise disposed of, a space elevator could not be safely constructed. Serious weather poses a threat to the section of cable that lies within the atmosphere and the radiation of the Van Allen belts could ablate and degrade the cable material or interfere with sensitive electronics on the climbers travelling through them. Vibration along the length of the cable could also pose an issue, potentially getting out of control if something were to stimulate the cable at its resonant frequency. Alongside all of these is the threat of a failure cascade, where the failure of a single section of cable could lead to failure in another section, and so on, until you have. In the event of the cable breaking, there would likely be little damage on the ground due to pieces of cable either burning up in the atmosphere or slowing down significantly due to their low density. The amount of space debris potentially caused by a failure on this magnitude could potentially be disastrous however, and could in theory result in a Kessler Syndrome cascade of debris generation.

All of these potential risks aside, the potential benefits an operational space elevator could provide could be quite far reaching. It has been estimated that a space elevator could carry payloads to GEO for the price of $220 per kg, compared to the average of $25,000 per kg to GEO with conventional rocket systems. Such a low cost to orbit would open up space to nearly any private institution, potentially leading to a sort of renaissance in the space industry. The cost of a single space elevator numbers in the billions of dollars, but would be significantly less for each subsequent space elevator built afterwards, due to most of that initial investment going to research and development of the necessary technologies. In addition, an interplanetary launch platform at the elevator counterweight could allow exploration of our solar system on an unprecedented scale.

It is my proposal that before we seek to create a space elevator on Earth, we should create one on the moon. Although the moon revolves so slowly that a synchronous orbit around it is impossible, we could instead use the Earth-Moon L1 or L2 Lagrange points. The moon is tidally locked to the Earth, meaning that the same side of the moon is always facing towards the Earth, so the L1 and L2 points remain stationary in relation to the surface. The moon with its 1/6th Earth gravity, no atmosphere, and practically no orbital debris would make an ideal place for space elevator construction. Both Lagrange points are further from the moon's surface that GEO is to Earth's surface at 56,000 km and 67,000 km respectively, but due to the moon's reduced gravity, the cable could be made of common industrial materials like Kevlar (Pearson et al, 2005), instead of experimental materials like carbon nanotubes, and a tapering of the cable would not be necessary, simplifying design and construction. Lunar regolith and other minerals could be mined from the surface and carried to L1 to be picked up and returned to Earth, or used in in space manufacturing. In addition, once one cable is connected to the equator, a second could be connected to a lunar base near one of the poles where the mining of water ice could take place. If such an in-space fabrication infrastructure could be developed, the reduced transit energy from the moon to Mars could help jumpstart exploration of the red planet. Engineers could then use the knowledge and experience gained from this venture, as well as the in-space construction capabilities in the construction of an elevator on Earth.

Space elevators, while a thing of science fiction for many decades, could hold the key to our future endeavors in space near Earth and beyond. There are a number of challenges that must be overcome before we can get there, but these challenges are far from insurmountable. The start of construction on a real space elevator, either here or on the moon, will likely begin within our lifetimes, and when finished will revolutionize space exploration and commerce.

# Appendix C: Solar Sail Propulsion

One major frontier in space exploration technology is that of solar sails, also known as light sails, which utilize the miniscule pressure generated by sunlight over large thin membranes analogous to sails to generate small amounts of thrust over long periods of time, producing great total acceleration using no fuel. Solar sail technology is still being tested and only a couple of solar sail powered craft have been successfully launched and deployed, but the technology has the potential to offer a wide range of benefits in the field of space exploration and research. There are however a host of unique engineering problems that must be solved before solar sail technology can enter widespread use.

The basic principle that allows solar sails to function is that while photons have no mass, they still carry momentum, which they can transfer to objects that they impact. The momentum of a photon or flux of photons can be expressed by the function: $p = E/c$ where p is the momentum of the photon or flux, E is the total energy of the flux, which can be determined by its wavelength, and c is the speed of light. The resultant pressure from this momentum is based on the number and energy of photons as well as the angle between the normal vector of the sail and the radial vector from the sun. The average solar pressure at a distance of 1 AU has been calculated to be about 4.5 $\mu N/m^2$ or 4.5 μPa for a surface with perfect absorptivity, and twice that for a surface with perfect reflectance (Nave, n.d.). This is due to Newton's third law of motion which states that all momentum in a system must be conserved. When photons are reflected instead of absorbed, their total change in momentum is greater than if they were simply absorbed, and so the resulting change in momentum of the sail must be greater as well. Another result of this reflectance is that the force generated on the sail is produced along the normal vector to the sail, instead of simply along the radius vector of the sun. Perfect reflectance is not attainable in reality unfortunately, so realistic sails are treated as having a roughly 90% reflectance (Nave, n.d.). One unfortunate result of this imperfect reflectance is that the sail stops producing useful amounts of thrust at around a 60 degree angle between the normal vector of the sail and the incoming solar radiation, instead of at 90 degrees that we would expect with an ideal sail, restricting the possible thrust vectors usable by a solar sail craft. Radiation pressure, while seemingly minor is something that must always be accounted for in interplanetary trajectories. The Messenger craft actually used solar radiation pressure to make minor course corrections more precise than would have been possible with its engines, by adjusting the angle of its solar panels (MESSENGER Sails on Sun's Fire for Second Flyby of Mercury, 2008).

Despite this disadvantage in comparison to spacecraft with traditional propulsion systems, solar sail craft offer a number of unique uses that would not be possible with those propulsion systems. One such possibility is that of dynamic satellite orbits, where a satellite controls the precession of its orbit using a solar sail system, potentially allowing it to remain along the sun-earth line at positions closer to the sun than the sun-earth L1 Lagrange point. Satellites in such orbits could help give warning of major space weather phenomena much farther in advance as well as detect Near Earth Objects (NEOs) in heliocentric orbits below 1 AU, which would otherwise not be detectable from Earth. Another concept is that of satellites in a halo orbit around the poles of a body, using a solar sail system to counteract the force of gravity. Another, perhaps more practical use would be small solar sail arrays used for station keeping or other small trajectory modifications for stations and satellites, allowing them to retain their orbits without propellant. Another potential use of a solar sail propulsion system is as a cheap, reusable interplanetary transfer system. A solar sail apparatus could attach itself to a payload, haul the payload to its destination (Mars orbit for example), then detach and return to Earth, ready to haul another payload. Another potential use would be that of an interstellar craft, by utilizing the fact that solar radiation pressure is related to the square of the distance to the sun. In theory, if one could design a craft able to withstand the extreme temperatures and radiation, a solar sail craft could perform a "sun dive" to a point below 0.05 AU and potentially accelerate to a significant fraction of the speed of light, which could allow us to reach our nearest neighbor Alpha Centauri within a few hundred years (Solar Sail Technology Development, n.d.). Such a design is not currently feasible but offers an exciting look into the potential future of solar sail technology.

Unfortunately, solar sails bring with them a number of engineering challenges to solve, in the construction, deployment, and configuration of the sails. The composition of the sails is perhaps the most important factor in their design, as they must be lightweight, highly reflective, and they must be able to survive great temperature variations, solar wind particles, and solar radiation. They must also be able to survive the strains of launch and deployment and must be able to maintain structural stability in the event of micrometeorite impact. In the past, sails have typically been made up of 5 micron sheets of Mylar or Kapton, covered in a thin film of aluminum, though there have been a number of different materials proposed that could yield greater strength at a lower density, including carbon nanotube meshes (Solar Sail Technology Development, n.d.). Deployment of the solar sail once the craft has reached orbit is also a significant challenge, as the sail must be lightweight and thin enough to fit inside a quite small space within the craft, and must be fully unfurled without tearing or otherwise deforming. NASA's Jet Propulsion Laboratory tested three major sail configurations when first exploring solar sail technology. The first is a square sail design made up of three triangular pieces of sail secured with long struts extending from each of the four corners. The next design, known as the Heliogyro was of four long, thin sections of sail deployed from rollers and kept taught with angular momentum as the craft spun. The third design was of a spinning disk of sails, again kept taught by the angular momentum of their spinning, as well as masses between each of the sail sections (Solar Sail Technology Development, n.d.). There have also been clover shaped designs that have been tested and met with mixed success. In addition to all of these challenges, the nature of the propulsion method and the previous 60 degree limit of thrust severely restricts the types of maneuvers that a solar sail craft can perform, and makes standard orbital maneuvers like the Hohmann transfer impossible, complicating the trajectory calculations.

Despite these major challenges, solar sails remain an attractive option for the future of space exploration, opening up new avenues of exploration and discovery that would otherwise be unobtainable.

# Appendix D: Telescope

There are several types of telescopes that astronomers and astrophysicists rely on to gather data for their research. The main categories include radio, infrared, visual, x-ray, and gamma ray telescopes. The most well-known type is the visual or optical telescope which relies on visual light to work. These are further broken down into refracting, reflecting, and catadioptric subtypes ("It takes more than one kind of telescope to see the light - NASA Science"). All of these types of telescopes depend on different types of information put off by astronomical features and are subject to a decrease in accuracy for various reasons. The possibility of locating at least one if not several types of telescopes on the lunar surface would greatly increase the knowledge we have about the universe and could prove to be enormously beneficial ("A Moon-Based Telescope | MIT Technology Review").

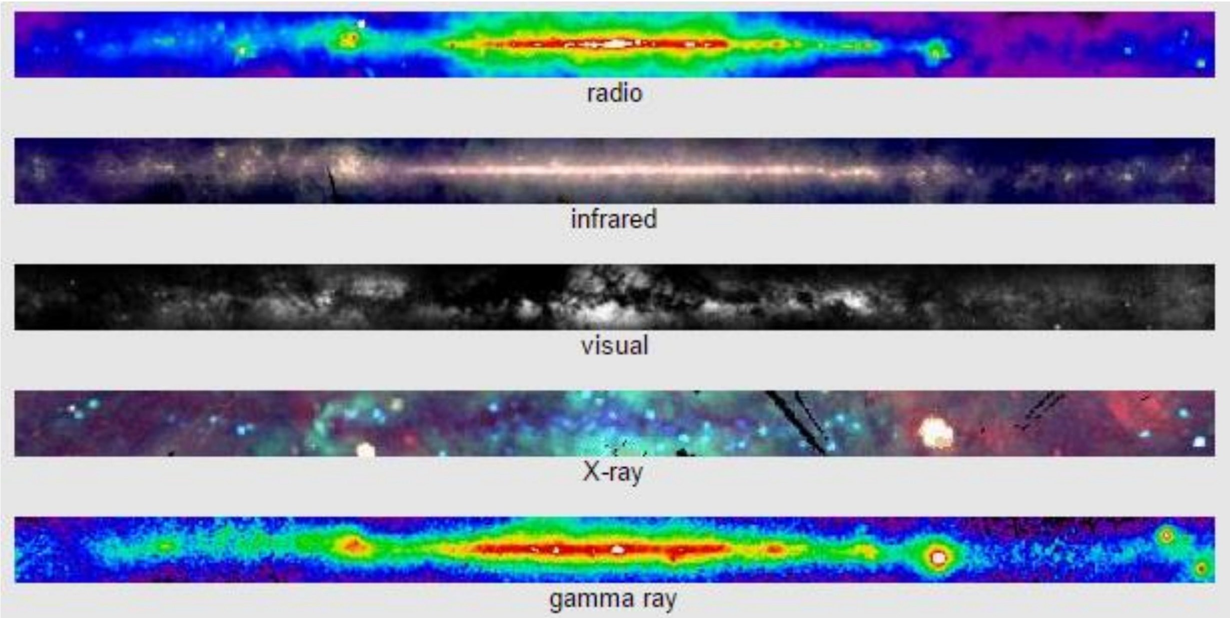


*Figure 34: readings from the different types of telescopes ("It takes more than one kind of telescope to see the light - NASA Science")*

Firstly, Moon's nearly negligible atmosphere (it does have one, but the amount of atmosphere per cubic centimeter there would constitute as a good vacuum here on earth and is quite comparable to that of density of the outermost fringes of Earth's atmosphere) would eliminate much of the need for costly adaptive optics technology. It would also aid in more accurate readings in gamma and x-ray telescopes as these signals can often be interfered as Earth's atmosphere disrupts and weakens these short wavelengths. The lack of Earth's weather that causes viewing problems as well as damage to facilities would also prove to be very beneficial.

*Figure 35: A radio telescope (Mount Pleasant Radio Observatory)*

Even if these complications did not exist on earth, there is the inherent problem associated with terrestrial viewing of light interfering with the ability to collect data with telescopes. On the far side of the moon, it would be very easy to avoid the inability to preform astronomic experiments associated with the earth day, where scientists are prevented by sunlight. Even with the lack of sunlight, terrestrial observers must navigate light pollution caused by manmade light sources and ironically enough, the Moon.

Of course these issues have already been at least partially addressed by space-based telescopes. However, a lunar based telescope is potentially better than space-based telescopes as while both can escape the Earth's atmosphere, a lunar based observatory would not have the added cost of steering. There are also fewer potentially hazardous conditions on the lunar surface making it very likely that a lunar telescope would last much longer considering everything orbiting around the earth that could be collided into. Additionally, space-based telescopes generally add to the already prevalent and undesirable "space junk".

That is not to say that having a lunar based telescope is perfectly ideal and does not present its own challenges. Micrometeorites strike randomly though infrequently, cosmic and solar radiation can slowly damage vital observatory instruments, then temperature shifts as large as 350 degrees Celsius and radiation could be hazardous to future human servicing missions. Lunar dust could pose problems for service missions as well as interfere with telescope operation. There is also the costs associated with getting the material to build the telescope and further missions to perform maintenance procedures (Jeanna Bryner, 2015).

There are however, several ways to possibly navigate special obstacles posed by the moon and potential hazards that may occur. Firstly, one proposed design for an optical telescope on the moon would be for a liquid mirror telescope to be constructed. At around 1% of the cost of a conventional optical telescope, it may be quite possible to allow in the budget for an extremely large telescope using this method. Typically these telescopes work by spinning a liquid, causing it to assume a parabolic shape such that it can reflect the light. The main issue with this, is that most liquid mirror telescopes use mercury for the liquid. This is for several reasons: it's is very dense so it would be quite expensive to launch, it's expensive to acquire, and it would evaporate quickly when expose to the lunar vacuum. A solution to this is to use a type of organic compound called

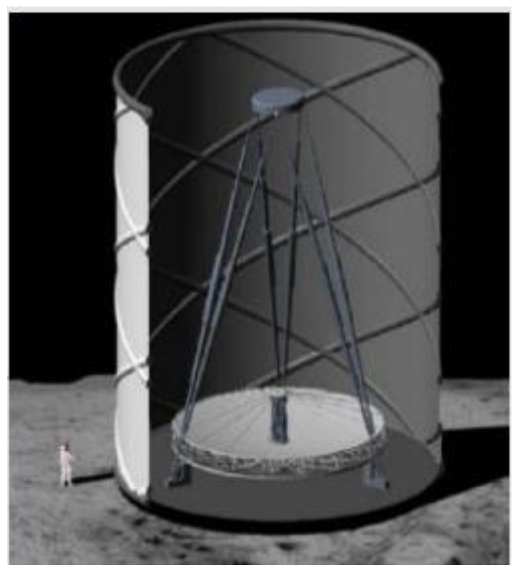

*Figure 36: Liquid mirror telescope ("Liquid Mirror Telescopes on the Moon – NASA Science")*

ionic liquids. They remain liquid at very low temperatures and their evaporation rate is nearly negligible. But even still, liquid mirror telescopes cannot be tilted away from the horizon, limiting their use. Methods are now being to electromechanically warp secondary mirrors suspended above the liquid mirror that could mitigate this issue. If this could work then the fact that the mirror always points up would actually be an advantage as it simplifies construction, and reduces mass by eliminating heavy mounts, gearing, and pointing-control systems needed for a steerable telescope ("Liquid Mirror Telescopes on the Moon - NASA Science").

Another method involves a design that could be implemented by using lunar resources for the building materials. Peter Chen, a physicist at the NASA Goddard Space Flight Center, and his team used a mix of epoxy, simulated lunar dust and carbon nanotubes to demonstrate how to use materials already found on the moon. With this mixture he was able to make a material that can flex or change shape when an electric current passes through. He used this as the foundation of a foot long disk and then poured more epoxy on top. This was then spun at a constant rate (much like the liquid mirror telescope would have to do to operate) until the epoxy hardened. This created the desired parabolic shape. A thin coat of aluminum was then applied in a vacuum to create the reflective surface.  With this method, making a Hubble sized telescope would require bringing 60 kg of epoxy to the moon with 1.3 kg of carbon nanotubes and less than 1 gram of aluminum, while the majority of the needed material (around 600 kilograms of lunar dust) would originate from the moon itself. Not only is this cost

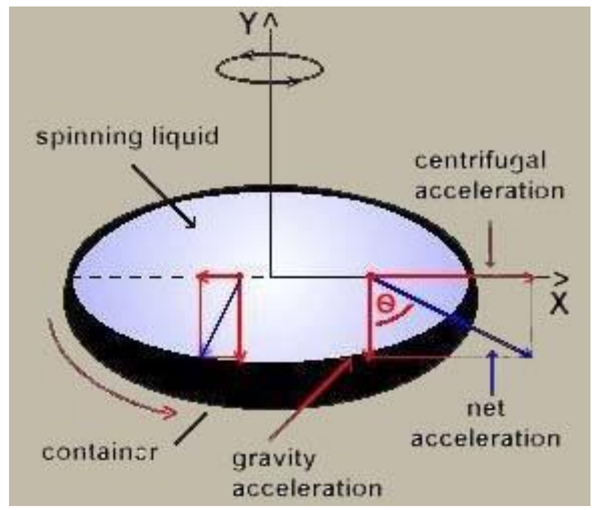


*Figure 37: Physics of the creation of the paraboloid in the aforementioned types of telescopes ("Liquid Mirror Telescopes on the Moon – NASA Science")*

effective, the vacuum of space would also be conducive to the necessary conditions to make the mirror (Jeremy Hsu, 2015).

# Appendix E: Lunar radiation

Radiation is a prevalent physical phenomena experienced on a daily basis. It is not always dangerous, as the risks it poses depending on the strength, type, and length of exposure. On the moon however, it poses a great risk, and proper mitigation techniques are essential to life there. Radiation can occur as particles or as electromagnetic waves. Particle radiation is, in general, made up of 3 types of particles: alpha (α) particles, beta (β) particles, and neutrons. Alpha particles are energetic helium nuclei with a +2 charge and a mass of 4 amu. Beta particles are electrons and can have either a -1 or +1 charge and have a mass of .000549 amu (β particles with a +1 charge are referred to as positrons.). Solar wind and Cosmic rays are examples of particle radiation. Electromagnetic radiation is composed of photons. This includes x-rays (produced from transitions of electrons between electron orbitals) and gamma-rays (produced by transitions of nucleons in the nucleus) ("Ionizing & Non-Ionizing Radiation").

The spectrum of electromagnetic radiation (Fig. 38) can be broken up into two basic categories: Ionizing and nonionizing. Radiation that has enough energy to move around atoms in a molecule or cause them to vibrate, but not enough to remove electrons, is referred to as "non-ionizing radiation."

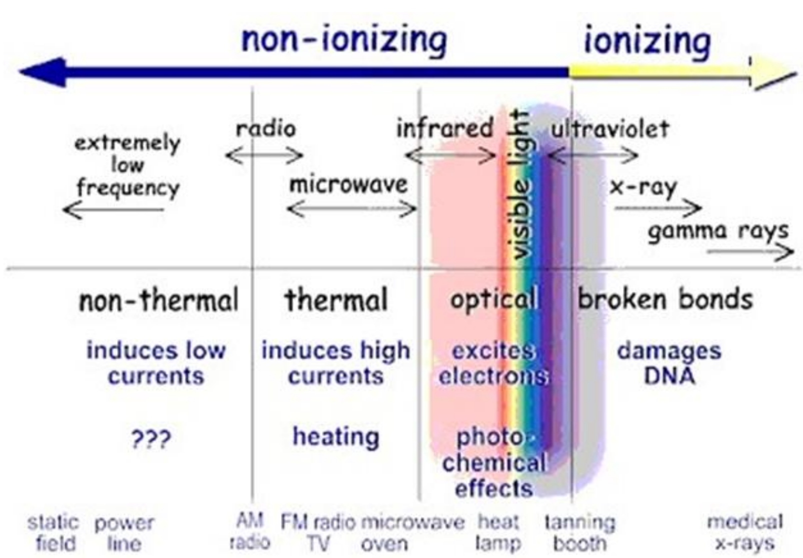


*Figure 38: The electromagnetic radiation spectrum ("Ionizing and Non-Ionizing Radiation")*

Examples of this kind of radiation include visible light and microwaves. Radiation that falls within the "ionizing radiation" range has enough energy to remove tightly bound electrons from atoms, thus creating ions. This is the type of radiation that people usually think of as 'radiation.' We take advantage of its properties to generate electric power, to kill cancer cells, and in many manufacturing processes.

On Earth, Humans are protected from radiation originating in space by atmospheric and magnetic shielding (Fig. 39) as our atmosphere can interact with the incoming particles while the magnetic field can divert them causing the displays known as the auroras. In space however, astronauts and their surroundings are at constant risk of much greater radiation exposure without this natural barrier. Beside the continuous exposure to galactic cosmic rays (GCR), exposure from particles emitted in unpredictable Solar Particle Events (SPE) may occur. A solar particle event or "proton storm," occurs when particles (generally protons) emitted by the Sun become accelerated to very high energies either close to the Sun during a solar flare or in interplanetary space by the shocks associated with coronal mass ejections. Apart from protons, these events may include other nuclei such as helium ions and HZE ions. These high energy protons and ions lead to several effects. Energetic solar protons are a significant radiation hazard to spacecraft and especially astronauts, who can receive large amounts of absorbed dose from the ionizing radiation. SPEs show an enormous variability in particle flux and energy spectra and have the potential to expose space crew to life threatening doses of radiation.

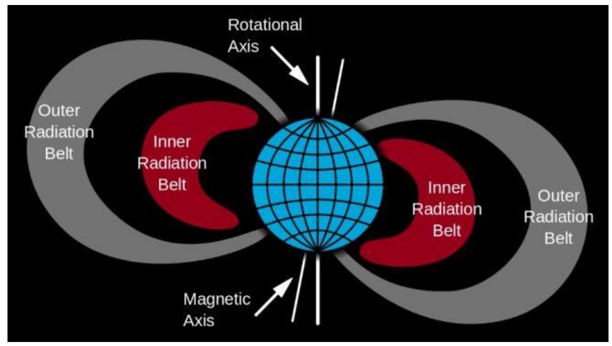

*Figure 39: the Van Allen Radiation Belts (Adrian, 2013)*

On Earth, the contribution to the annual terrestrial dose of natural ionizing radiation of 2.4 mSv by cosmic radiation is about 1/6, whereas the annual exposure caused by GCR on the lunar surface is roughly 380 mSv and 110 mSv (Staff, 2012).

Further understanding than we have of the radiation environment of the moon will be essential during endeavors to expand prolonged space flight and colonization beyond LEO (low earth orbit). However, possible mitigation techniques are available and may eventually provide a feasible way for further expansion to happen. Potential candidates include the use of lead, gold, water shielding, a thick layer of regolith over any habitat, and many more. One reason for the use of lava tubes (sub-surface tunnels on the Moon that are believed to have formed during basaltic lava flows) as the location of a structure would be the natural radiation protection they would provide. Results from the NLSI Lunar Science Conference in 2008 show regolith to be effective against Cosmic Galactic Rays, based off the positive results they received with the ions they tested ("Radiation Shielding Properties of Lunar Regolith and Regolith Simulant"). Another idea that has not been as greatly explored is the potential of creating a local magnetic field around the settlement. Energy on the moon will be inexpensive given the vast resources available on it and the reliable access to solar power. While colonizing in a lava tube will give radiation and micrometeorite protection, a local magnetic field would protect the entire settlement and any needed areas not covered by regolith that may need access to natural sunlight ("Moon's Mini-Magnetosphere").

# Appendix F: Lunar Water

In order for colonization to be possible, the ability to access water and other resources will be vital, and will thusly play a large part in choosing a location. It is known that there is water along with many other useful materials on and beneath the lunar surface. However, further investigation of the properties of the lunar regolith must occur if colonization is to be successful. The following outlines what inspection of the moon's properties has yielded and suggestions for further gathering of information.

It is now known that there is water on the moon, but the question of how much still remains unanswered. In 2010, a mission involving the LCROSS (lunar Crater Observation and Sensing Satellite) found that there is not just evidence of water on the moon, but of a complete water cycle. While it is possible that the lunar water came from the impact of a comet a very strong possibility of the water cycle exists and would work in the following way: The hydrogen ions in the solar wind could chemically combine with the oxygen atoms present in the lunar minerals (oxygen has been found to make up approximately 45% of the lunar surface).Such events can be observed in the case of s Sulphur oxide which is present on the lunar surface. Hydrogen ions would combine with the Sulphur oxide to produce Sulphur hydroxide. Sulphur hydroxide would combine to produce water and Sulphur compounds. This can be shown in the following way:

$$2\ S\text{-}OH \longrightarrow S{=}O + S + H_2O$$

or

$$2\ S\text{-}OH \longrightarrow S{-}O{-}S + H_2O$$

The presence of the elements associated with water is not only vital in their drinking form but also for other processes such as the creation of rocket fuel. Therefore an extensive analysis of the resources in lunar regolith is essential for multiple processes in colonization.

Lunar water appears to be in the form of pure ice crystals in several places on the moon, but the most notable find of water on the moon has been from the plumes generated on impact by LCROSS and in the Cabeus crater. These plumes were found by the sensors carried by the satellite to contain mostly water ice and volatiles (compounds that freeze in the lunar craters) such as methane, ammonia, hydrogen gas, carbon dioxide, and carbon monoxide. Light metals were also found such as sodium, mercury and possibly silver.

A concurrent mission with LCROSS was that of the LRO which provides information on the lunar surface through several means. One of the main considerations that were taken in the design of this mission which should most likely be applied to further missions was LRO's polar orbit. This is useful for 2 specific reasons: polar orbits go around the celestial body vertically while the celestial body rotates horizontally, thus providing maximum visibility of the surface and polar orbits are also ideal because as given in their name they provide observation of the celestial body's poles which given several properties of the lunar poles (they avoid the long lunar nights and are exposed to the sun continuously), these are the most likely candidates for areas that would be optimal for colonization. On board the LRO, there are six different instruments meant to measure radiation, create 3d mapping of the lunar topography, and detect possible near-surface water ice deposits. The latter is done with LEND (lunar exploration neutron detector. LEND provides high resolution hydrogen and hydrogen-bearing compounds (such as water ice) distribution maps with a spatial resolution of 10kmin diameter. LEND has nine detectors that measure thermal, epithermal and fast neutron fluxes. By incorporating the capabilities of

LCROSS and LRO, through measurements of water concentration and temperature along with the mapping of hydrogen in the area, it was confirmed that water may reside in pockets in and outside the shadowed regions of the crater (Phillips, 2010).

Despite the success of these missions, the question of whether there is enough lunar water to sustain a colony remains unanswered. Robert Zubrin, president of the mar society is quoted saying "The 30 m crater ejected by the probe contained 10 million kilograms of regolith. Within this ejecta, an estimated 100 kg of water was detected. That represents a proportion of ten parts per million, which is a lower water concentration than that found in the soil of the driest deserts of the Earth. In contrast, we have found continent sized regions on Mars, which are 600,000 parts per million, or 60% water by weight." Other specialists in this field have estimated this particular impact site to contain 5.6 ± 2.9% water ice. Later in 2010, NASA reported water at the north pole of the moon estimated to be at least 600 million tons of ice, but in 2014, new findings have shown the actual figure to probably be significantly less (Messier, 2009).

Further investigation of lunar water will therefore need to occur. As of now, there are several ongoing missions and plans for missions to do this. An emphasis will be placed on not only determining how much water there is, but optimal methods for mining it. Currently, the lunar flashlight project is planned to begin in 2017 or 2018. This will be a CubeSat mission where after deployment; the satellite will unfurl an 840ft solar sail. If successful, this will be used for propulsion and also as an instrument to send back readings about the lunar surface to be analysis. This device has been described as a “mirror” as it works such that the sunlight will be bounced off of the sail into the permanently shadowed regions of the craters, and then collected by a passive infrared spectrometer which will detect wavelengths that are indicative of water frost. This will indicate the location of surface water. Another method is to directly drill into the regolith and collect samples from the surface. This will definitively show scientist how the water may be distributed in the lunar soil. The Resource Prospector Mission (RPM) plans to do exactly that by equipping a rover with a neutron spectrometer to measure water concentrations up to one meter underground and a near-infrared spectrometer to make surface measurements (Wall, 2012).

# Appendix G: NEO Deflection Techniques

The consequences of an asteroid impact on Earth are severe. The impact of a 10 km asteroid is largely accepted as the reason for the mass extinction of the dinosaurs and many other species around 65 million years ago. More recently, the explosion of a 20 m meteorite over Russia caused over 1,000 injuries and major damage to buildings (Kuzmin, 2013). While the chances of a major impact are low, the potentially catastrophic effects dictate the need for a method of deflection potentially hazardous objects.

Two main ideas for deflecting potentially hazardous objects exist: impulsive deflection and slow push deflection. Impulsive deflection exerts a large force on the object over a small duration using explosives or through a kinetic impactor. Slow push deflection exerts a small force on the object over a long period of time using focused light, tugs attached to the object, or a gravity tractor (NASA, 2006).

For explosive deflection, an explosive payload rendezvouses with the asteroid and detonates to alter the object's trajectory. Conventional explosives would not be effective for this application because of their low energy released to mass ratio. Lifting the required mass of explosive to rendezvous with an asteroid would be difficult or impossible with current rocket technology. However, nuclear explosives are much more efficient as they are able to deliver the equivalent of 1,000 – 2,000 kg of TNT per kg of explosive mass. A nuclear bomb would be able to deliver enough energy to an asteroid to deflect its course significantly (NASA, 2006). The use of nuclear explosives in space would face political challenges due to treaties on the use of nuclear weapons in space.

The explosive can be planted under the asteroid surface, detonated upon impact with the asteroid, or detonated at a certain distance away from the asteroid. Planting the explosive under the surface is the most efficient option, but it is likely to destroy the asteroid and spread debris which could still impact the earth. The safest option is standoff detonation, or the detonation of the explosive at a certain distance from the asteroid surface. This method is still capable of diverting the asteroid's course enough to avoid collision when using nuclear explosives. Also, this method does not require any information about the asteroid's spin or composition, allowing it to be used quickly in an emergency (NASA, 2006).

Another option for impulsive deflection is the kinetic impactor. No explosives are used in this method; instead a vehicle is accelerated to a velocity of 10-50 km/s relative to the asteroid. When the vehicle hits the asteroid, the asteroid's course is changed. Some information about the asteroid's composition is necessary for this technique as an impact with a soft surface would not be effective (NASA, 2006).

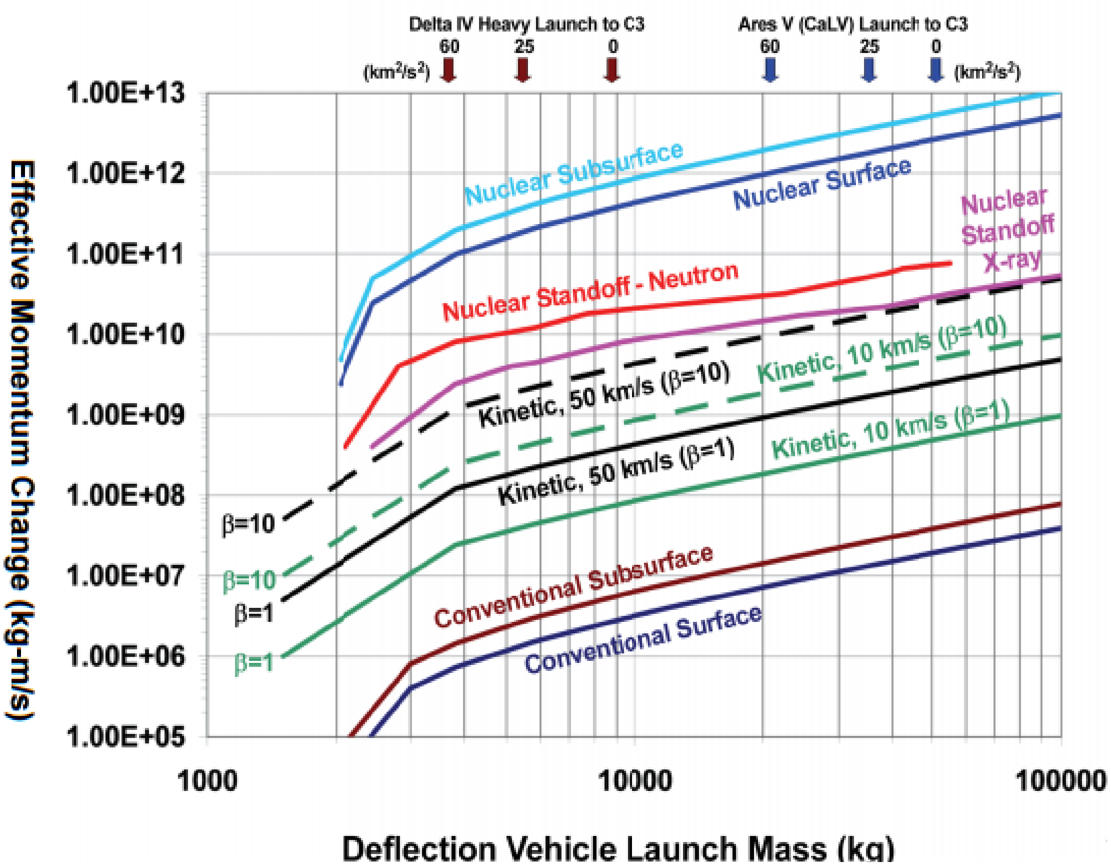


*Figure 41: Efficiency of impulsive deflection techniques (NASA, 2006)*

Figure 41 shows that nuclear explosives are the most efficient deflection technique, followed by kinetic impact and then conventional explosives.

The first form of slow push deflection is the use of focused light to heat the surface of the asteroid. When the surface is heated, material is burned off and ejected into space, providing a change in course for the asteroid. A spacecraft equipped with mirrors can focus sunlight at the asteroid in order to accomplish this. Alternatively, a nearby spacecraft could shine a powerful laser at the asteroid to heat the surface.

Another form of slow push deflection involves landing a probe on the asteroid surface. This requires information about the asteroid's spin and composition. Designing a mechanism to keep the craft attached to the asteroid could also prove difficult. A tug is a probe that provides thrust to the asteroid using its own engines. A mass driver is another type of probe that does not use fuel, but instead mines material from the asteroid and ejects it to change the asteroid's course.

Lastly, a gravity tractor could be used to divert an asteroid. A gravity tractor is a spacecraft that maintains a certain position relative to the asteroid using its thrusters. The craft will exert a small but constant gravitational force on the asteroid, which will eventually pull it away from collision with the Earth. The exhaust from the tractor's engines must not contact the asteroid, or it will provide an acceleration in the wrong direction.

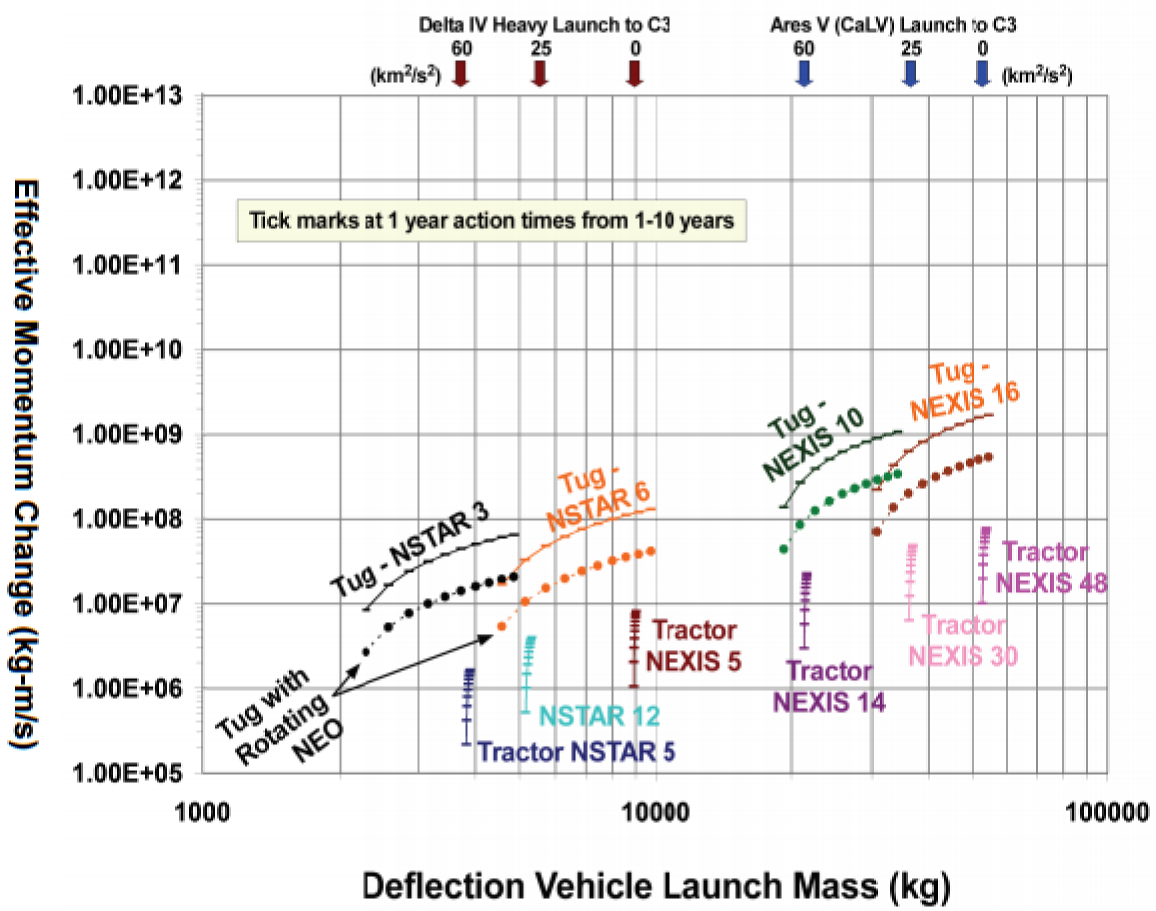


*Figure 42: Efficiency of Slow Push Techniques (NASA, 2006)*

As figure 42 shows, the tug is the most efficient form of slow push deflection. However, the nuclear explosive deflection remains the most efficient method overall.

# Appendix H:  Gravitational Effects on Humans

Several processes rely on Earth's gravity in order to be carried out with favorable outcomes. These processes can affect the growth, development, and maintenance of several elements. These include, but are not limited to: embryonic development, maintenance of muscle condition, and gravitational cues to orient one's self. In order for human exploration of space to be successful with minimal damage to astronauts, these effects must be thoroughly studied and plans must be made to mitigate them.

At roughly a fourth of the size of earth, the gravitational forces acting on masses located at the lunar surface will be much less than that of masses on the Earths. To be exact, the gravitational force experienced will be 83.3% less ("The Moon's Gravity - How Much You Would Weigh on the Moon?"). Weakening or atrophied muscles is one concern that comes with lower gravitational forces. Less of a load on the leg and back muscles can leave subjects weak. The bones can also suffer significant damage. When the force on bones due to weight is reduced significantly for extended periods of time bone breakdown will begin to occur. This is due to how the process of ossification, the process of laying down new bone material by osteoblast cells, decreases due to a lack of stress on the musculoskeletal system, while bone resorption, the process by which osteoclast cells break down bone and release minerals in them, increases ("Background Information on Bone Health."). Overall, this leads to net decrease in bone density. Without the slight compression between the vertebrae of the spinal column due to gravity, the disks can also expand and cause lengthening in the spine, making the astronaut taller. This can lead to back pain ("The Body in Space.").

Further problems in the body can occur with issues in fluid shift and the cardiovascular system. In space, bodily fluids such as blood can redistribute towards the upper body, without the downward pull of gravity, away from the lower extremities. This decreases the circumference of the legs and may cause puffiness in the face. The main discomfort of this condition can occur when the fluids shift to the head and cause feelings of congestion. In the cardiovascular system, most functions continue to behave normally. However, the heart does not have to work as hard in the lower gravity environment which may lead to deconditioning and decrease in the size of the heart.

Along with these complications, the lack of Earth gravity can cause disorientation both psychologically and through physical means which manifest psychologically. This can be seen most dramatically in the effects it has on balance, vision, and body orientation in terms of location and direction. A complex integrated set of neural circuits allow for humans to maintain these functions as the brain receives and interprets information from numerous organs such as the eyes, inner ear vestibular organs, and senses from the muscles and joint. The pattern that the brain relies on from these organs drastically changes with the difference in gravity. This can cause disorientation and increased clumsiness, increasing the risk of falling and injuries (Gannon, 2014).

Apart from the health of the humans that arrive from earth to a colony, low gravity could have a very distinct effect on the long term population in regards to fetal development. There have been several mixed results regarding exactly how a lower gravity environment may affect embryonic development, but the most recent study on mammalian embryonic development in simulated microgravity suggests that there is a significantly better chance a female mouse carrying to term in 1g over her microgravity counterparts. In this study, microgravity led to an overall reduction in the rate of blastocyst formations after the first 96 hours of culture. The conclusion was that these blastocysts revealed that the differentiation of embryonic cells into trophectoderm was drastically impaired. Trophectoderm is the essential tissue that nourished the embryo and ultimately contributes to placenta formation. This seems to be consistent with a 1979 mission that showed that rats can become pregnant in space, but are seemingly incapable of bringing the pregnancies to term. It may be that it is simply much harder for them to. It was also unclear as to what stage the complications occurred. Further research is being done to determine what magnitude of gravity is necessary for normal reproduction to occur. This will determine whether it may be successful on the Moon and Mars ("Embryonic Development-lost in Space?").

As of now, there are very few methods for mitigating the effects of lower gravity. Astronauts currently exercise to maintain their muscle mass. In order for humans to survive on the moon, a suggested strategy is to develop a concurrent nutritional system specialized to maintain muscle condition and increase bone strength. Currently, on the ISS, astronauts are not given supplements, but designing an experiment to see how effective a nutritional supplement would be, could give great insight into how the condition of a large population of lunar colonists could be maintained. This however, would still not replace the benefit of exposure to earth-like gravitational conditions.

Currently there is only one known way to generate artificial gravity. This method relies on rotation of a body to create a force due to rotation that would mimic the effects of gravity. The following equation represents the force due to rotation:

$F=(mv^2)/r$

Where m is the mass of the object, v is the velocity of the object ($2\pi r/p$), r is the radius of the circle, and p is the period of the rotation.

If this method were to be used in a settlement, it is suggested that rotation rates remain at one revolution per minute or less. Subjects are predicted to become ill at rotation rates greater than three revolutions per minute. For this method to be employed, it is also suggested that shapes with circular cross-sections be used. Examples of this include toruses, dumbbells, spheres, cylinders and other shapes incorporating configurations of aforementioned structures ("ISSDC Training: Artificial Gravity.").

This method is ideal for free-orbiting settlements, but for a lunar colony, engineers will not have the luxury of working with a whole structure that can be rotated. A proposed design for a lunar colony may be enhanced then by a feature that could use these basic principles to provide an environment with similar benefits. An example of this could be a torus shaped structure around the parameter of a crater that generated spin perhaps by running a train on the inside or somehow rotating itself along a track. Inhabitants could strap themselves in and then once proper spin was achieved, they would be able to walk around in a gravitational environment that would be the same as on earth.